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GRAPHIC VISUALIZATION OF SIMULATED DOWNSTREAM WAKES GENERATED BY VARIOUS HIGH-SPEED HULL FORMS

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Abstract

The downstream turbulent wakes of surface ships are numerically simulated by the parabolic marching computer code SURFWAKE. This code solves the incompressible time-averaged Navier-Stokes equations with a two equation (K, ε) closure model for the turbulence, and a "rigid-lid" approximation to the free surface. Graphic software are developed for two and three dimensional visualization of the results for velocity, turbulence kinetic energy and Reynolds stress. These programs are designed for user-friendliness and compatibility with the output of SURFWAKE. Results for the following three ship models are presented: a twin-screw (inward-rotating) frigate, a single-screw frigate, and a twin-screw (inward-rotating) containership. Visualization of these results bring out several interesting features of the numerical simulation. We have attempted to distinguish wake characteristics based on the hull features. Simulation over a large distance downstream for the single-screw frigate reveals that the propeller wake does not rise to the free surface.

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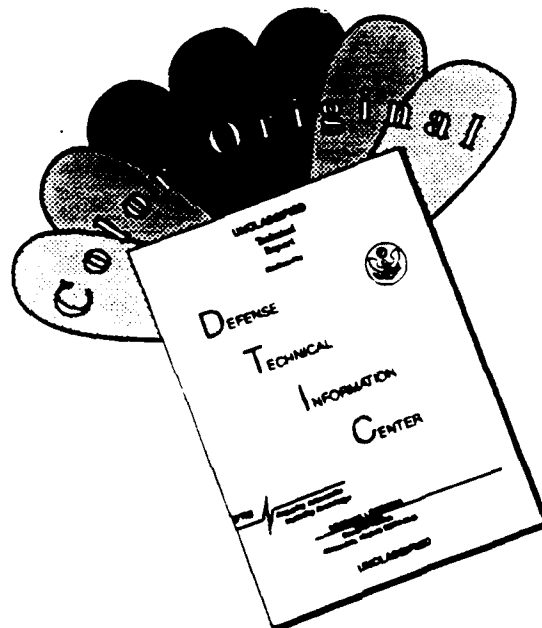
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1. INTRODUCTION

The downstream turbulent wakes of surface ships can be numerically simulated by a number of codes. One of the codes currently in use at the Naval Research Laboratory (NRL) is SURFWAKE, as described in Miner et al. (1988). This code employs a parabolic marching algorithm based upon the incompressible time-averaged Navier-Stokes equations combined with a two equation (K, ε) closure model for turbulence. Miner et al. (1988) have concluded that SURFWAKE is a suitable code for wake calculations, when the "rigid-lid" approximation to the free surface is used. They have identified the need for further work on the code when using a linearized free surface boundary condition. Meng et al. (1985) and Miner et al. (1988) have given details about the computational model used and the input-output formats of the program.

The SURFWAKE code requires nearwake initial plane data for the three components of velocities and the turbulence kinetic energy (TKE) as input. Typically this data is obtained from measurements in the wake of complete ship hull models. Experiments were conducted using a variety of scale models as described in Hoekstra and Ligtelijn (1991). The hull variants include three tankers, three cargo vessels and three high-speed naval vessels.

The experimental data set employed in the present study consisted of initial and downstream data planes which were forwarded to the University of Michigan via NRL by Lindenmuth (1990). An intermediate stage of data analysis which provided initial data planes suitable for the SURFWAKE numerical simulations was performed at NRL.

The original objectives of the present project are explained below:
1. Execution of SURFWAKE with the "rigid-lid" boundary condition and to obtain downstream values of the mean streamwise velocity, the swirl velocity vectors, turbulence

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kinetic energy and Reynolds stress distribution for selected configurations presented by Hoekstra and Ligtelijn (1991). For some of the vessels, it was also desired to run SURFWAKE for a long distance downstream in order to obtain details about the far-field wake flow.

2. Development of graphic software for two and three dimensional visualization of the results obtained from the SURFWAKE simulations.

3. Analysis of the visualized results and possible comparison with the ship wake measurements performed by Hoekstra and Ligtelijn (1991) and obtained subsequently from NRL and DTRC.

The first step of the process was acquisition of the code SURFWAKE and installation of it in the Department of Naval Architecture and Marine Engineering Stardent computers. The program was compiled, debugged and executed on sample data described by Miner et al. (1988). Upon completion of this step, the project continued in a bi-directional mode. The graphic programs were developed at the University of Michigan in parallel with receiving data for different configurations from NRL. Towards the end of the project, the near-field wakes of three hull configurations were simulated and analyzed graphically. These were:

Configuration 71: twin-screw (inward-rotating) frigate,

Configuration 81: single-screw frigate,

Configuration 61: twin-screw (inward-rotating) containership.

In addition, for Configuration 81 the far-field wake flow was also simulated. Different graphic programs developed and/or used for this work are elaborated in Sec. 2 of this report. Briefly, they are the following:

isosrf   -   Program to draw three dimensional iso-parametric surfaces of a given property field.

trace   -   Program that draws path lines of chosen particles in a given velocity field.

`contour` & `MPLOT/ISOX` - Two-dimensional contour plotting program.

`vector` - Program that draws two-dimensional vector plots at any cross-section of the flow.

In analyzing the results, we attempted to identify distinguishing hydrodynamic features of the wakes generated by different ship hull configurations. We have observed the simulated wake patterns on the free surface, and in particular whether the computer code predicts the rise of the propeller wake to the free surface far downstream of the vessel.

Section 2 of this report gives details of the graphic programs developed during this project. No attempt has been made to discuss the details of SURFWAKE, as they are already presented in Miner et al. (1988). The results obtained using SURFWAKE for the three above-mentioned configurations are presented and discussed in Section 3. Appendix A is designed to serve as a user's manual for the four graphic software packages.

2. DESCRIPTION OF GRAPHIC SOFTWARE

The programs developed as part of this project are mainly run in the Stardent graphic supercomputers and on the Apollo 3500 Series machines of the Department of Naval Architecture and Marine Engineering. Execution of SURFWAKE was usually done in the Stardent computers due to their speed and memory availability. The output format of SURFWAKE was modified to produce the data required for three dimensional plotting. A summary of the graphic software and the CPU time taken by each program for a sample session is tabulated in Table 1.

2.1 isosrf - Iso-surface Plotting Program

This program was written originally to visualize turbulent channel flows by Han (1990). Iso-parametric surfaces characterized by a constant value of a given property, are three-dimensional analogs of contour lines. In this program wireframe models are used for the visualization of iso-surfaces. The wireframe surfaces are created by the surface tiling method (Han, 1990). The program requires two input files, i.e. the grid file which contains the x, y and z coordinates of the spatial grid, and the property file which contains property values at all points in the grid. Upon input of the files, the program keys into a user-friendly graphic menu system. Options available in the menu system are summarized in Fig. 1. Different iso-surfaces may be displayed by clicking on the color bar which is part of the menu system. The program can also create data files of any iso-surface for display on the Applied Visualization Systems (AVS) program resident on the Stardent.

2.2 trace - Path Tracing Program

This program also employs a similar input format as isosrf, requiring three property files for the three components of the velocity field. This program resorts to a graphic menu system (Fig. 2), where the user can identify particles in a chosen cross-plane. The program calculates the successive positions of the particle in time by a centroiding procedure. The time step is currently set at 0.005 (diag) / Pmax, where

$$diag = xmax^2 + ymax^2 + zmax^2,$$

and Pmax is the maximum value of the plotted property i.e., velocity.

Two versions of the program currently exist in the Stardent machine. The first version was written as a general purpose program to read in a vector field and draw path lines. The second version of the program reads in a vector field as measured from a ship moving at a constant speed in the negative x direction. The path lines are drawn as viewed from an earth-fixed coordinate system. The latter version is obviously found to be more suitable for

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examining SURFWAKE velocity fields. Access details of the two versions are given in Appendix A.

2.3 contour & MPLOT/ISOX - Two-Dimensional Contour Plotters

The MPLOT/ISOX program is a general purpose user-friendly contour plotting program developed by Professor K.-P. Beier at the University of Michigan. The program is resident in the Apollo computers. Detailed documentation on this program is available in Beier (1986). contour is a liaison program between SURFWAKE and MPLOT/ISOX. This program adopts an alphanumeric menu system, described in Fig. 3. The user can choose one variable among the three velocity components and the TKE. A special feature of this program is that the user can select any principal plane in the grid to view the contours. Thus for example, one can successively view different cross-sections of a wake and also free surface contours. Plotting of the contours and making hard copies are done as part of the MPLOT/ISOX menu system, with details in Appendix A.

2.4 vector - Two Dimensional Vector Plotting Program

This program reads in the output of SURFWAKE and draws vector plots at any location in the grid in one of the three principal planes. This user-friendly program is constructed using the graphic subroutines of the MPLOT package, with details given by Beier (1986). After drawing the first vector plot, the program switches to a graphic menu system, where the user can travel along the axis viewing successive vector plots, or even go backwards and view plots of the previous planes. In the continuous mode of operation, the program draws vector plots of successive planes till the end of the grid is reached. Depending on the speed of the computer the output appears dynamic, changing in real time. The program has options for changing practically every aspect of the presentation of the plot, as shown in Fig. 4.

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2.5 Compatibility and Array Size Limitations

Both of the two dimensional plotting programs are executed in the Apollos, and the three dimensional plotting programs are executed in the Stardent machines. The programs contour and vector are compatible with SURFWAKE, and the user need not create any special data files. The output of contour is designed for MPLOT/ISOX, so the user merely switches back and forth between the menu systems of MPLOT/ISOX and contour, to view and make copies of different contour plots. The three dimensional programs were designed as more general purpose, and hence a linkage program was developed to convert output of SURFWAKE to the input of isosrf and trace. Details are given in Appendix A.

The limitation on the grid size for isosrf is 50 x 64 x 50 and for trace is 160 x 40 x 40. These sizes are based on memory and CPU availability for each of these programs. All the SURFWAKE runs conducted during this project were thus restricted to a maximum of 160 output planes downstream of the ship. From Miner et al. (1988), this implies the parameter TIMEMX is set at 159, since SURFWAKE always writes the output of the initial plane data. Thus one can execute the program as far downstream is desired, but output is obtained only at 159 locations. This can be done using the parameter NFREQF (Miner et al., 1988). It was determined however, that beyond a certain distance downstream the SURFWAKE code develops numerical instabilities, as described in Sec. 3.

3. ANALYSIS OF RESULTS

The wake flow quantities of interest presented in this section are defined below, and the reader is referred to Miner et al. (1988) for more information. These various quantities are :

mean streamwise velocity	$\dfrac{u}{U_0}$,

transverse velocities $\quad\dfrac{v}{U_0},\ \dfrac{w}{U_0}$,

turbulence kinetic energy $\quad\dfrac{1}{2}\left(u'^2 + v'^2 + w'^2\right)$,

Reynold's stress components $\quad\dfrac{u'v'}{U_0^2},\ \dfrac{u'w'}{U_0^2}$;

where

U_0 uniform speed of the ship,

u, v, w mean velocity components of the flow,

u', v', w' fluctuating velocity components of the flow.

3.1   Configuration 71

This is a twin-screw frigate with slightly inclined propeller shafts. The propellers rotate in an inward sense. Rudders are fitted behind the propellers. This hull generates side vortices but no bilge vortices (Hoekstra and Ligtelijn, 1991). This is explained as being due to the hull having a pram-type afterbody. The model ship parameters that are pertinent to the present study are summarized in Table 2.

Streamwise velocity contours of this vessel are shown at the initial and final planes in Figs. 5 and 6 and a few iso-surfaces are plotted in Figs. 7 and 8. Positive values of streamwise velocity are seen in the propeller wake and most negative values are present on the free surface. The core of the propeller wake appears to have moved downward between these downstream locations as is evident from the figures. In Fig. 6, a strong shear region appears to be concentrated in between the propeller core and side vortex. This region is also apparent in the iso-surface plots, and exhibits very high positive velocities wrapped in very

high negative velocities. This type of shear region is not visible initially, but develops after traveling a few beams downstream. While we observe that diffusion tends to average the flow over the rest of the cross-section, it is contradicting that such a shear region would develop as we travel downstream. We then conclude that this might be a numerical error. The swirl velocity plots (Figs. 9 and 10) confirm the presence of the propeller slipstream and the side vortex. It is interesting to note that the the propeller slipstream has diffused more rapidly than the side vortex between the initial and final plane. Hoekstra and Ligtelijn (1991) have mentioned that the side vortices diffuse rapidly and only the rotation induced by the propeller in its slipstream is visible as a vortex-like flow.

The TKE and Reynolds stress plots at the initial and final plane are presented in Figs. 11 through 14. Higher values of TKE accompanied by higher values of Reynolds stress are now seen to be closer to the free surface than near the propeller slipstream. This is indicative of considerable wave activity on the free surface.

3.2 Configuration 81

Configuration 81 is a single-screw frigate with a central rudder. The propeller shaft is supported by a V-strut. Hoekstra and Ligtelijn (1991) point out that the bilge vortex pair generated by the propelled hull is not affected strongly by the shaft struts.

Figs. 15 through 31 show different properties of the near field and far field wakes of the vessel. Fig. 15 shows streamwise velocity contours at the initial plane ($x/B = 4.62$). There is a lack of port-starboard symmetry in the wake field in the vicinity of the propeller core. This asymmetry is due to the rotation of the single propeller, since the hull has port-starboard symmetry. Hoekstra and Ligtelijn (1991) also mention that the bilge vortices and the rudder can considerably enhance the asymmetry. The downstream wake is also asymmetric. Streamwise velocity contours at the final far field plane ($x/B = 294.6$) plotted

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in Fig. 16 show some interesting properties of the wake. The strong shear region evidenced in Configuration 71 is also seen here. This region starts at approximately x/B = 14.0 and develops downstream. The propeller wake is practically non-existent in Fig. 16. The reason for this is apparent in Fig. 17 which shows streamwise contours along the centerplane, y = 0.0. This figure shows that the propeller wake is projected downward and is diffused away within 120 beams downstream, resulting in the characteristic pattern of Fig. 16. For this configuration, the propeller wake does not seem to reach the free surface far downstream. This is also seen in Fig. 18 which shows streamwise velocity contours on the free surface. Figs. 19 and 20 show iso-surfaces from the initial plane to x/B=37.7. The plots show two views of the surfaces, and these views visualize the development of the propeller core and free surface near-field wake. Figs. 21 and 22 show far-field wake of Configuration 81 between x/B = 262.9 and 294.5. They show the presence of the shear region and also the absence of the propeller wake. The swirl velocity vector plot at the initial plane (Fig. 23) is similar to Fig. 9c of Hoekstra and Ligtelijn (1991), the oblique downwash of the bilge vortices due to the presence of the rudder is noted. Fig. 23 also shows very mild secondary vortex formation below the free surface. The downstream swirl velocity plot (Fig. 24) shows no significant velocity, except at the shear layer core. The TKE plots of Figs. 25 and 26 show that the maximum TKE is below the free surface at the center plane. With distance downstream the energy gets dissipated and turbulence spreads to a wider cross-section. The Reynolds stress vectors at the initial and final planes are shown in Figs. 27 and 28. The initial plane plot shows Reynolds stress activity of the order of 0.001, which is diffused away leading to negligible activity in the final plane.

3.3 Configuration 61

Configuration 61 is a twin-screw container ship with a single central rudder. The propellers rotate in an inward sense. Hoekstra and Ligtelijn (1991) mention that the central rudder

does not annihilate the propeller slipstream rotation, and the bilge and propeller vortices are almost coaxial.

Figs. 29 shows the streamwise velocity at the initial plane of the computational domain. The influence of the central rudder is seen in the drag wake contours, which are present below the propeller core, along the center line. Further downstream, the drag wake splits into two, with the propeller wake enveloped in the middle (Fig. 30). This is seen quite clearly in the iso-surface plots (Figs. 31 and 32). Regions of highly negative values of streamwise velocity are seen in red color. The swirl velocity plot of Fig. 33 show the initial presence of two vortices near the free surface. Both these vortices rotate counter to the propeller rotation, and they are present in the drag wake. While it appears that the vortex away from the centerline might be a side vortex, the vortex closer to the center line, above the propeller core might be caused due to the presence of the central rudder. This vortex appears to dissipate rapidly, as seen in Fig. 34.

TKE plots of Figs. 35 and 36 show magnitudes of the same order as seen in the previous two hull forms. However, in comparison with the TKE plots of twin-screw frigate (Figs. 11 and 12) higher values of TKE are deeper for Configuration 61, indicating lesser wave activity at the free surface. The Reynolds stress vector plots of Figs. 37 and 38 also point out to the same, with higher values in the region slightly above the propeller core.

3.4 Distinguishing wake features

In comparing the wakes of configurations 71 and 81, the effects of twin-screw vs. single-screw can be seen. Apart from the obvious presence of two propeller vortices vs. one propeller vortex, the downstream wake is influenced by the interaction of the propeller vortex and the side vortices. Single-screw ships are associated with wakes which have port-starboard asymmetries. The direction of propeller rotation also considerably influences

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the emerging wake patterns. Hoekstra and Ligtelijn (1991) mention that twin-screw ships generating bilge vortices have a quieter wake when fitted with outboard turning propellers. Configurations 71 and 61 can be compared based on the presence of the bulbous bow, and the influence of two rudders vs. one central rudder. Hoekstra and Ligtelijn (1991) mention that breaking of the bow wave creates a trail of high TKE, seen to be more pronounced in the configuration without the bulb. The presence of rudders in the propeller slipstream (Configuration 71) contributes to the partial removal of the propeller slipstream rotation. It also causes an oblique downwash of the bilge vortices. In contrast the presence of the central rudder in configuration 61 does not reduce the propeller slipstream. The central rudder also creates a vortex in the wake which rotates counter to the propeller vortex.

4. CONCLUSIONS

This report has presented details of a graphic software suite of programs designed to visualize the results obtained using SURFWAKE. The graphic software programs are available for both two and three dimensional visualization. Some of the programs are compatible directly with the output of SURFWAKE. Liaison programs are created for those software modules which are not compatible with the output of SURFWAKE. Special care is taken to ensure that the software are as user-friendly as possible.

The downstream turbulent wakes of three surface ship hull configurations have been simulated using SURFWAKE, and results are presented and discussed in this report. Distinguishing features of individual wakes influenced by single vs twin screw, presence vs absence of bulbous bow etc. are mentioned. Simulation of the far-field wake of the single screw frigate shows that the propeller wake does not rise to the free surface.

Appendix A of this report contains all necessary commands required to access and execute all the discussed software programs. This report thus also serves as a User's Manual for these programs.

5. ACKNOWLEDGEMENT

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Meng, J.C.S., Grant, J.R., and Uhlman, Jr., J.S., (1985), "Numerical Simulation of Turbulent Wake with a Free Surface," Gould Defense Systems Inc., GOULD OSD-771-HYDRO-CR-85-05.

Miner, E.W., Swean, Jr., T.F., and Troesch, A.W., (1988), "Evaluation and Additional Documentation of the Parabolic Marching Code Surfwake," NRL Memorandum Report 6331, Washington, DC.

APPENDIX A: USER'S MANUAL

The following section gives access and execution details for the following programs:
SURFWAKE (also called `bsurf.f`), isosrf, trace, contour and vector. Commands are
presented for both the Stardent and Apollo computers.

The most current version of `bsurf.f` is available in

`//chaos2/users/+research/surfwake.dir`

A subroutine module that creates output for graphics called `ksubr.f`, and a 'makefile'
also reside in the same directory. The makefile compiles `bsurf.f` and `ksubr.f` and
creates an executable file called `run`. Compilation and execution of `bsurf.f` are
recommended on the Stardent (because of speed and memory). Files can be transferred
from Apollo to Stardent through the File Transfer Protocol (FTP). The following sequence
is usually followed:

```
ftp hobie

.... (login)

cd /u/.. (directory name)

send bsurf.f

...

bye
```

One can also use the `get` command to transfer data files from the Stardent to Apollo.

Sub-directories exist in `//chaos2/users/+research/surfwake.dir` for
different models. The following is a list of available models and their directories:

Model#	Name	Sub-directory name
51	destroyer	ddg51
71	frigate twin-screw inward	frig71
81	frigate single-screw	frig81

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| 61 | container twin-screw inward | `cont61` |

It is advisable that when transferring data to Stardent similar model sub-directories be created.

A.1 Working on the Stardent

A.1.1 Executing bsurf

To execute the makefile, type

```
make
```

Before executing bsurf, the user is advised to move to a model sub-directory. To execute bsurf, type

```
../run < inputfile > outputfile
```

The 'inputfile' is the name of the file that contains the namelists required for bsurf. The first line of the namelist file contains the name of the initial plane data file. This file must also be present in the current sub-directory. The following table gives the 'inputfile' for each model. Some of these models have more than one file, with different grid sizes. Generally, the 'n' or 'w' in the file name denotes narrow or wide grid respectively.

Model#	File
51	`in51dat.dat`
71	`c71n_indat`
81	`c81n_indat`
61	`c61w_indat`

The 'outputfile' can be of any name (better to have current date on it), where the screen dump from bsurf will be stored.

It is important to note that the output array size defined in `ksubr.f` is 160 x 65 x 45. Three variables defined in the namelist file are important in modifying output files for

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graphic visualization. These are mentioned below and more details are given in Miner et al. (1988).

MAXCYC   maximum number of time steps computed by bsurf

TIMEMX   distance downstream at which execution will be terminated if MAXCYC has not been reached.

NFREQF   number of longitudinal time steps between writes of flow field information of the transverse plane onto ksubr arrays.

Generally we require MAXCYC/NFREQF $\leq$ 159. This incorporates the fact that bsurf always writes the initial plane information before time stepping.

Many output files are created for graphic visualization, and are listed below. Files with names beginning with 'u' are unformatted, and cannot be visually edited.

GRID.OUT   grid information

uQ.OUT   turbulence kinetic energy

uU.OUT   streamwise velocity

uV.OUT   horizontal velocity

uW.OUT   vertical velocity

uUU.OUT   Reynold's stress - x component

uUV.OUT   Reynold's stress - y component

uUW.OUT   Reynold's stress - z component

A.1.2 isocon - the post processor

The output of bsurf is not compatible with the file formats of isosrf and trace. An executable program called isocon (for iso conversion) reads the output files of bsurf and converts them to isosrf and trace format. The limitation on the data size for isosrf is 50 x 64 x 50 and for trace is 160 x 40 x 40. If the output of bsurf is less than 50 x 40 x 40,

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`isocon` reads the data file as it is. If not, the program prompts the user for the following parameters and modifies the data in any or all the three directions.

INITX/INITY/INITZ (integer)   starting value of x,y,z.

JUMPX/JUMPY/JUMPZ (integer)   interval between successive stations.

NXMAX/NYMAX/NZMAX (integer)   final values of x,y,z.

To access this program, type

      `../isocon`

The following are the names of the files created by isocon:

Output files of bsurf	Output files of isocon
uQ.OUT	uturb.k
uU.OUT	uvel.x
uV.OUT	uvel.y
uW.OUT	uvel.z
uUU.OUT	ustr.x
uUV.OUT	ustr.y
uUW.OUT	ustr.z

The program also creates a grid file called `GRIDD.OUT` only if the original grid file is modified.

A.1.3 `isosrf` and `trace` - details

The Stardent machines at the Department of Naval Architecture have two display heads. Commands in this section are applicable for display head 1. If using display head 2, `run` is replaced by `run1`.

To execute isosrf, type

      `run /u/swim/name/isosrf`

After entering the name of the input property file, the program switches to its graphic menu system.

Two versions of trace are available in the Stardent machines:

1.   The version in `/u/flow/han/trace.dir/ship.dir/trace` reads in a 3D vector field and draws path lines. This is a general purpose program.

2.   The version in `/u/flow/han/trace.dir/earth.dir/trace` reads in 3D vector field data as measured from a ship moving in the -x direction with a normalized speed of 1. The path lines are drawn as viewed from an earth-fixed coordinate system. This program is more useful for viewing bsurf output.

To execute the latter version, type

```
run /u/flow/han/trace.dir/earth.dir/trace
```

At the first prompt in trace, the user can type either `uvel.x` or `ustr.x`, and the other components are automatically read in. The graphic interface can then be used for further manipulations. We note in the passing that for changing grid plane in the program, the user has to click on an invisible strip at the lower left corner of the window.

A.2   Working on the Apollos

A.2.1 contour & MPLOT/ISOX and vector - details

The program contour can be accessed by typing

```
../contour
```

The user must create an additional shell (shift shell key) and type

```
/progs/mplot/isox
```

The input file for ISOX is called `ISOX.DAT` produced by contour. It is to be noted that one need not exit contour to use `ISOX.DAT`. Using the two menu systems, one can

consecutively view contours and make metafiles (for more details on metafiles, see Beier, 1985) at different planes in the grid. Once all metafiles are created, they can be converted to postscript files by typing

```
/progs/mplot/metips
```

and following the prompts. The postscript files are printed using the command

```
prf filename -pr plimsoll -trans
```

To access vector, type

```
../vector
```

TABLE 1. GRAPHIC PROGRAMS - DETAILS

PROGRAM	INPUT	OUTPUT	INTER-FACE	REAL TIME (min:sec)	CPU TIME (min:sec)
ISOSRF	u/v/w/Q	iso-parametric surfaces	graphic	4:39.2	3:38.2
TRACE	u,v,w grid plane particles	trajectories	graphic	3:35.9	1:31.0
CONTOUR	u/v/w/Q	input file for MPLOT/ ISOX	alpha	0:43.4	0:17.4
MPLOT/ ISOX	input file	contour lines	alpha	0:55.5	0:6.8
VECTOR	u,v,w grid plane	2D vector plot	alpha, graphic	2:56.4	0:53.5

TABLE 2. MODEL SHIP PARAMETERS

CONFIGURATION	61 CONTAINER SHIP	71 FRIGATE	81 FRIGATE
C_B	0.62	0.5	0.44
L/B	5.4	8.0	7.3
B/T	3.7	4.0	3.2
Speed (m/s)	2.0	2.0	2.0
Bulb	yes	no	no
Propulsion	Twin-screw (Inward)	Twin-screw (Inward)	Single-screw (Right handed)

```
                    ┌─────────────────┐
                    │  isosrf - menu  │
                    └─────────────────┘
```

alphanumeric mode

- make AVS file
- read new file etc.

surfacing method (Han, 1990)

color table

- 2 color
- 3 color
- 5 color

freeze

delete

rotate/zoom /pan

auto rotate

background color

exit
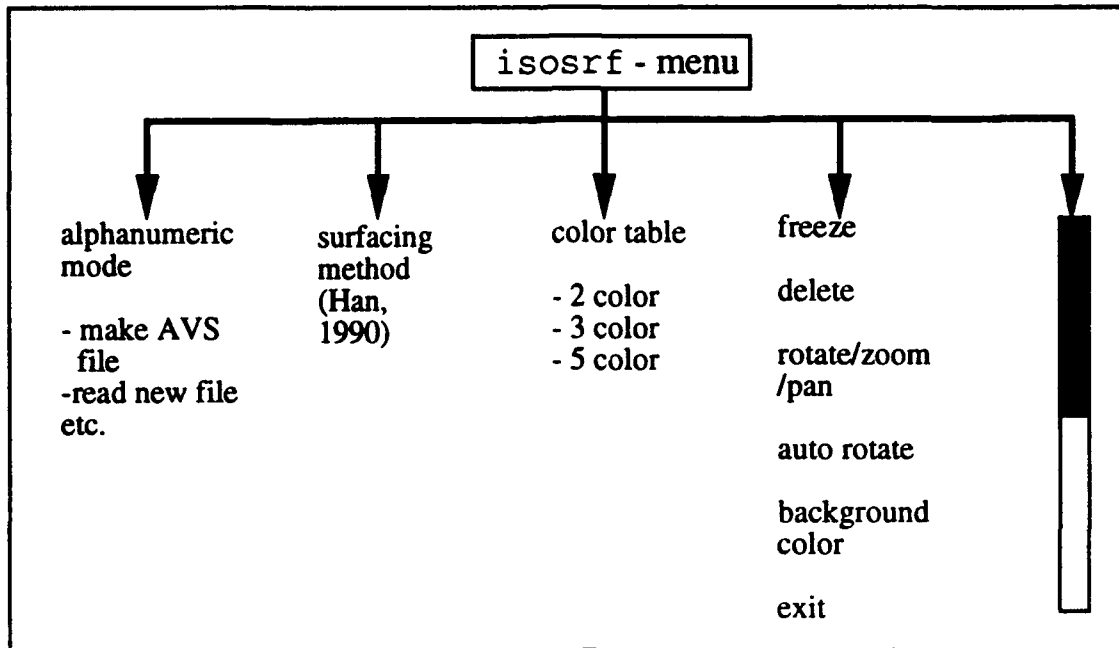
Figure 1. `isosrf` - menu system

```
                    ┌────────────────┐
                    │  trace - menu  │
                    └────────────────┘
```

select

- grid plane
- start point

trace lines

- draw
- clear

view

- rotate
- zoom
- pan

read new file

exit
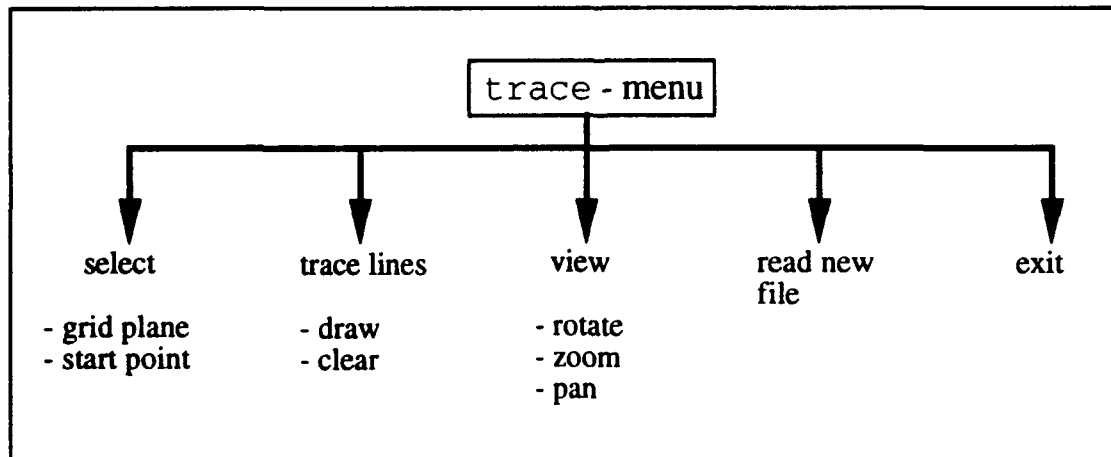
Figure 2. `trace` - menu system
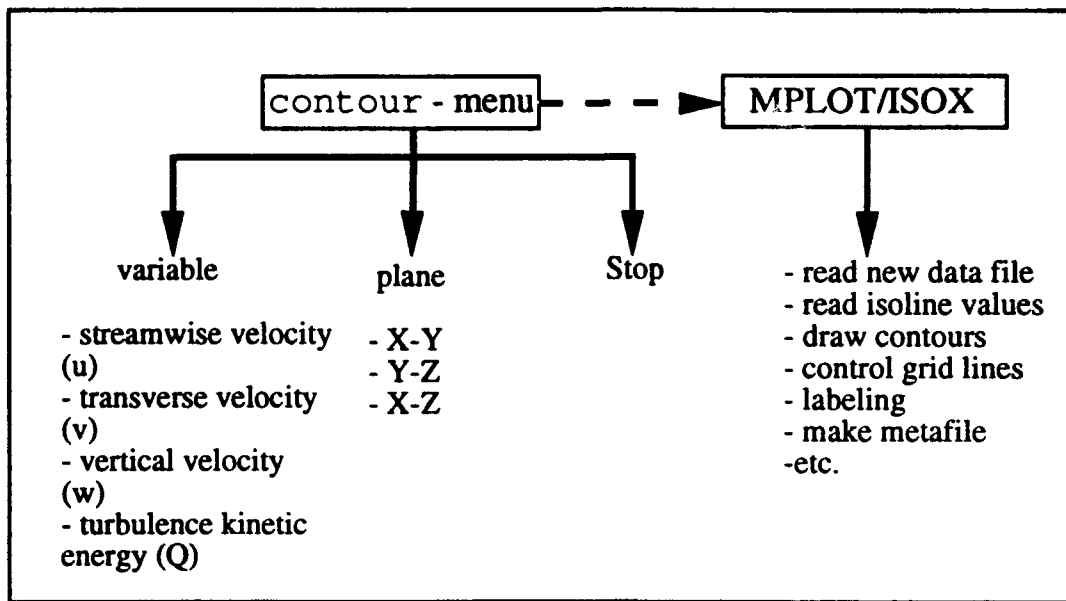
Figure 3. contour/ISOX - menu system
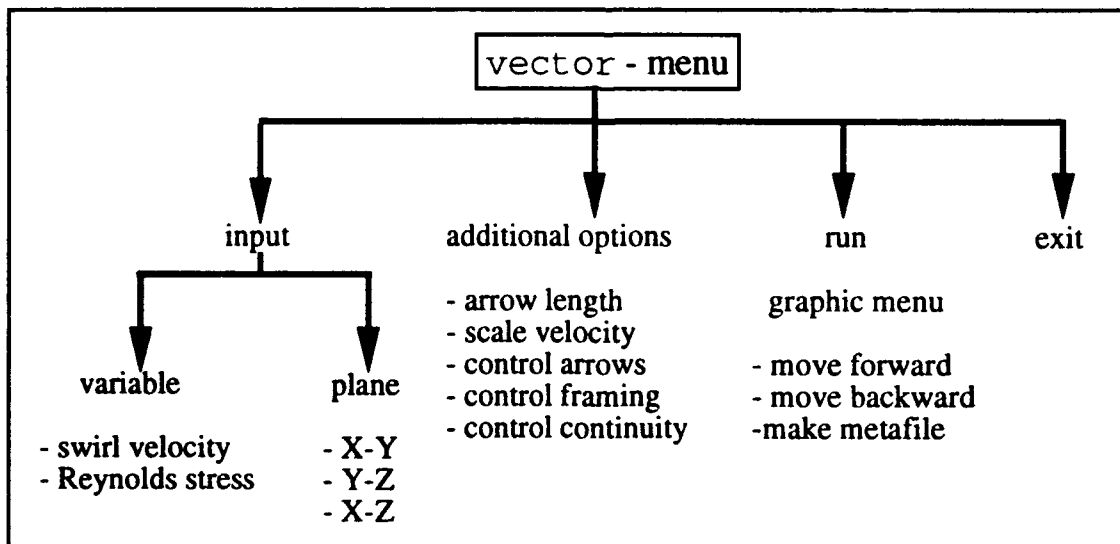
Figure 4. vector - menu system
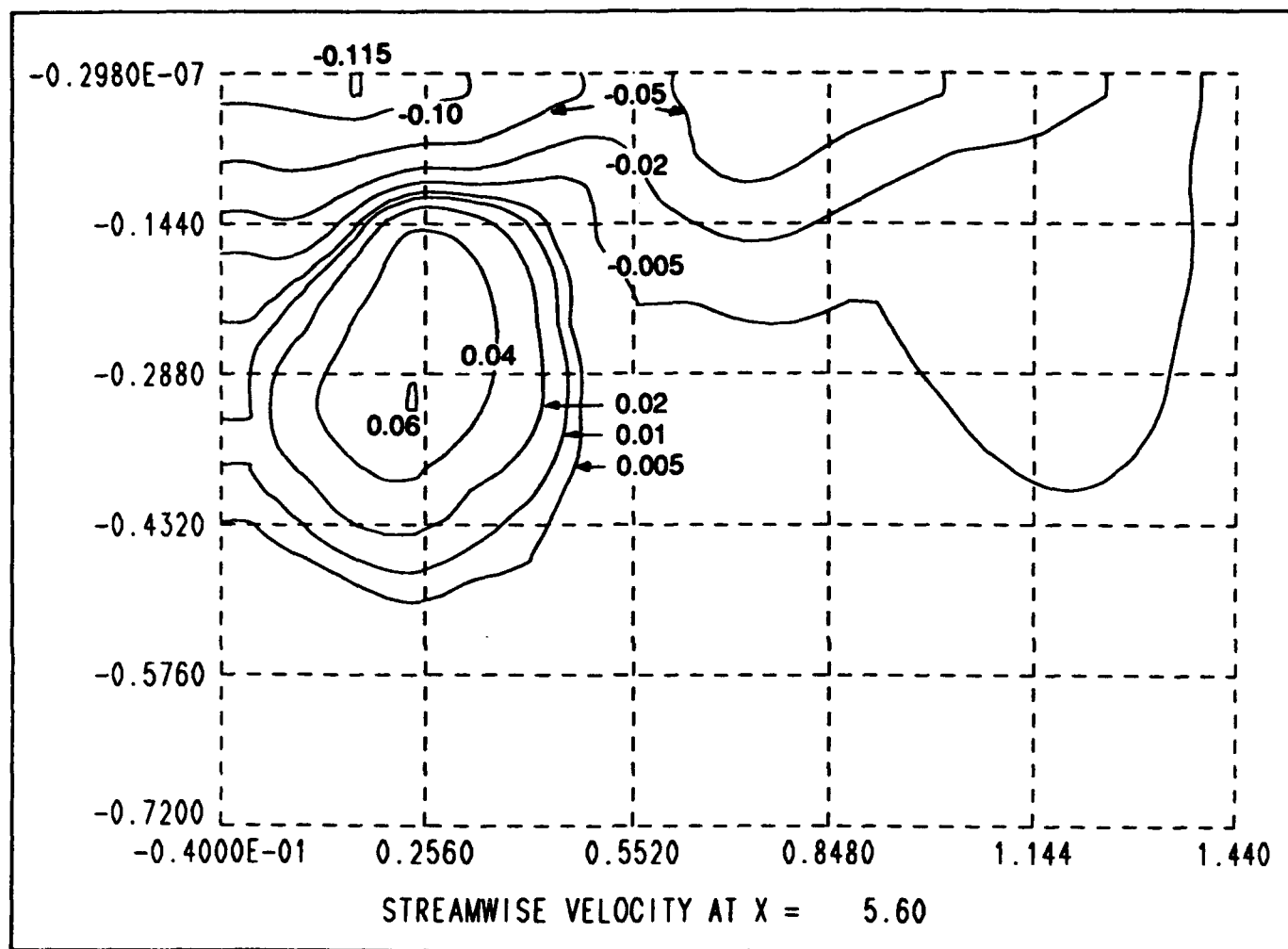
Figure 5.   Configuration 71: Streamwise velocity at x/B=5.60 (Initial plane)
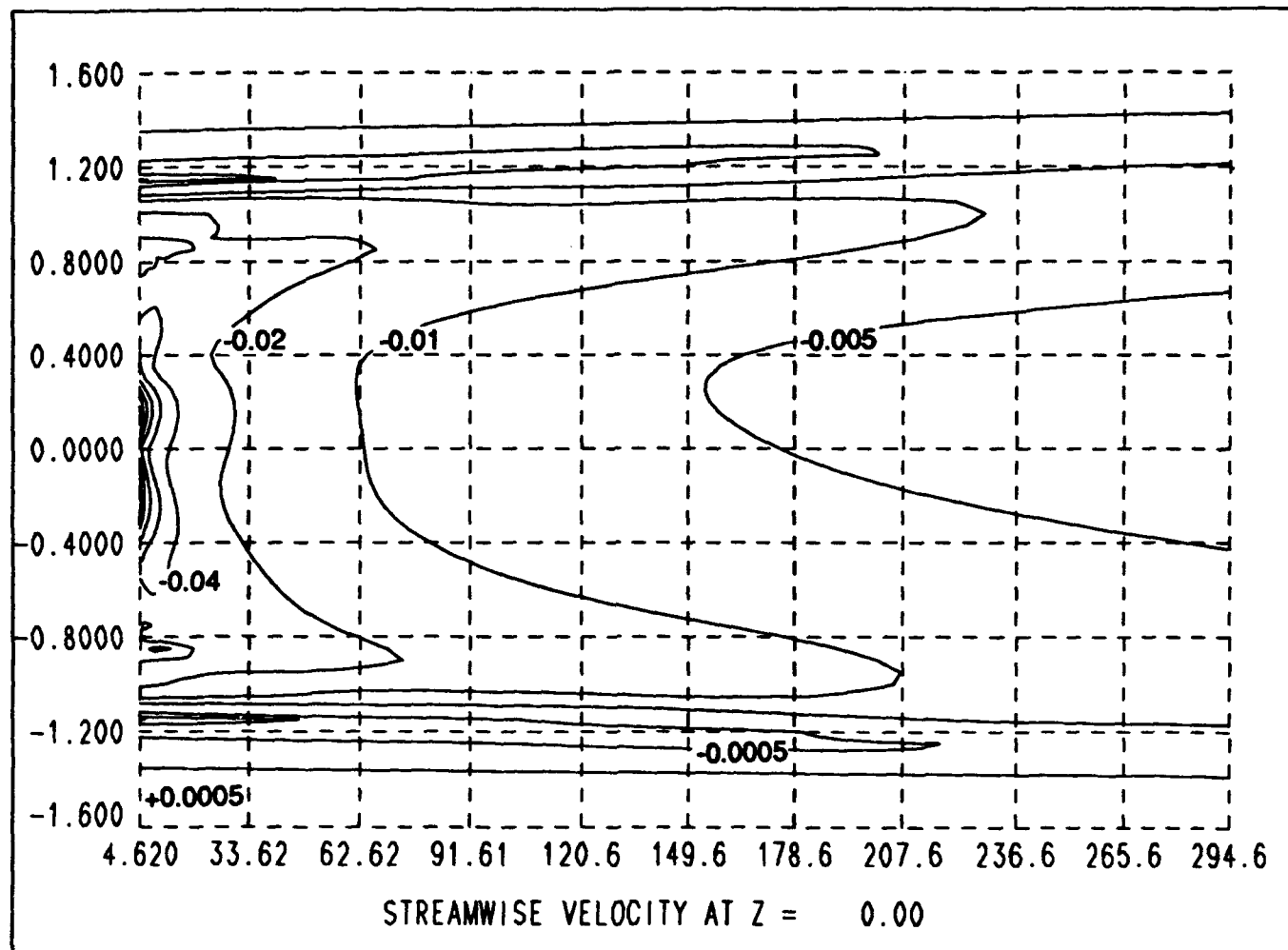Distances in beams
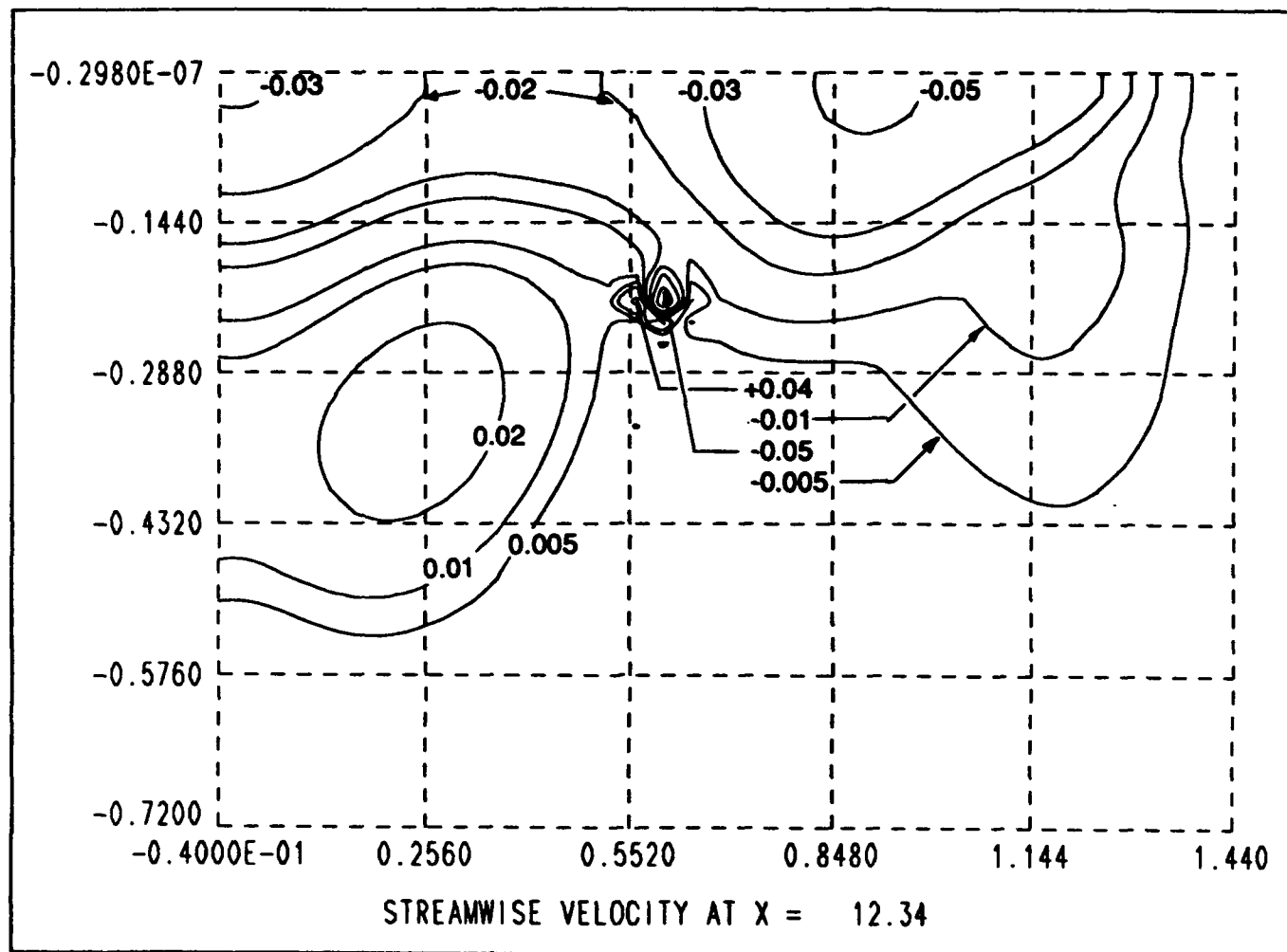
Figure 6.   Configuration 71: Streamwise velocity at x/B=12.34
              Distances in beams
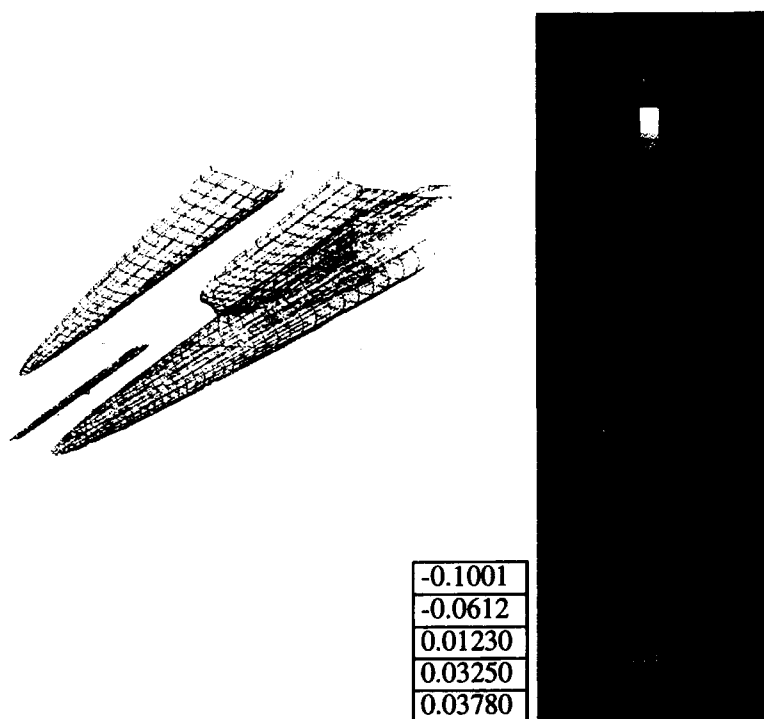
Figure 7. Configuration 71: Iso-surfaces of streamwise velocity
Distances in beams; PMIN=-0.1152, PMAX=0.0605
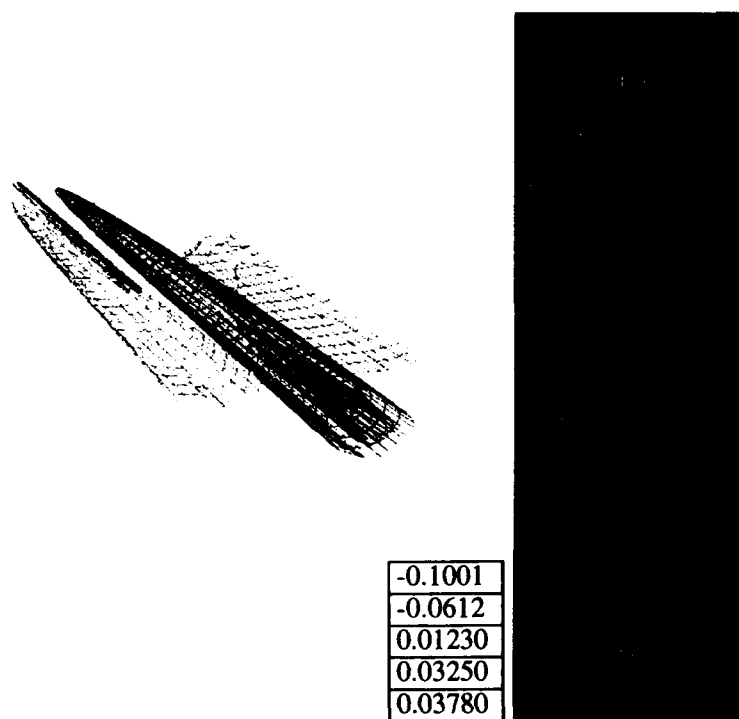
Figure 8. Configuration 71: Iso-surfaces of streamwise velocity
Distances in beams; PMIN=-0.1152, PMAX=0.0605
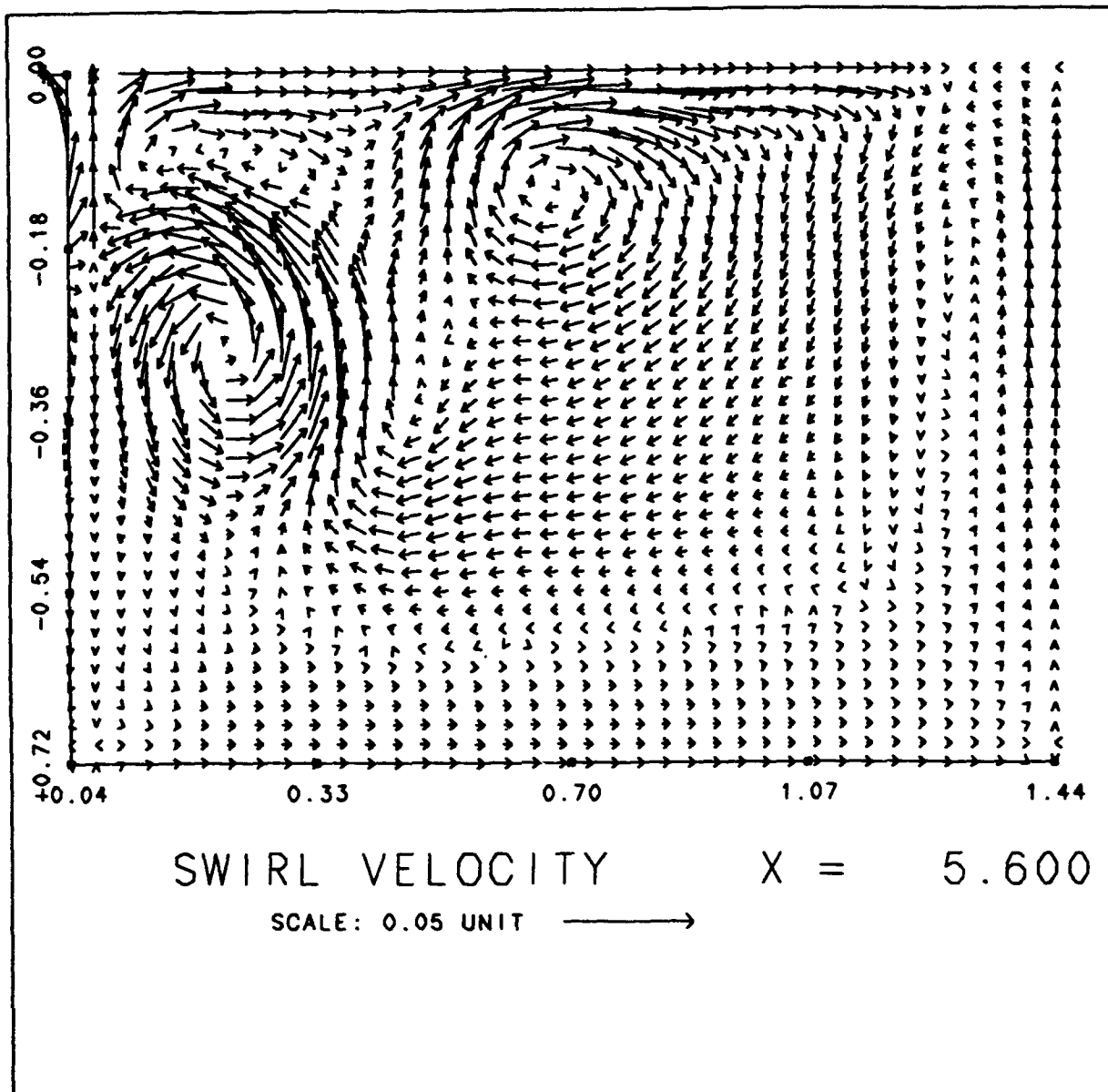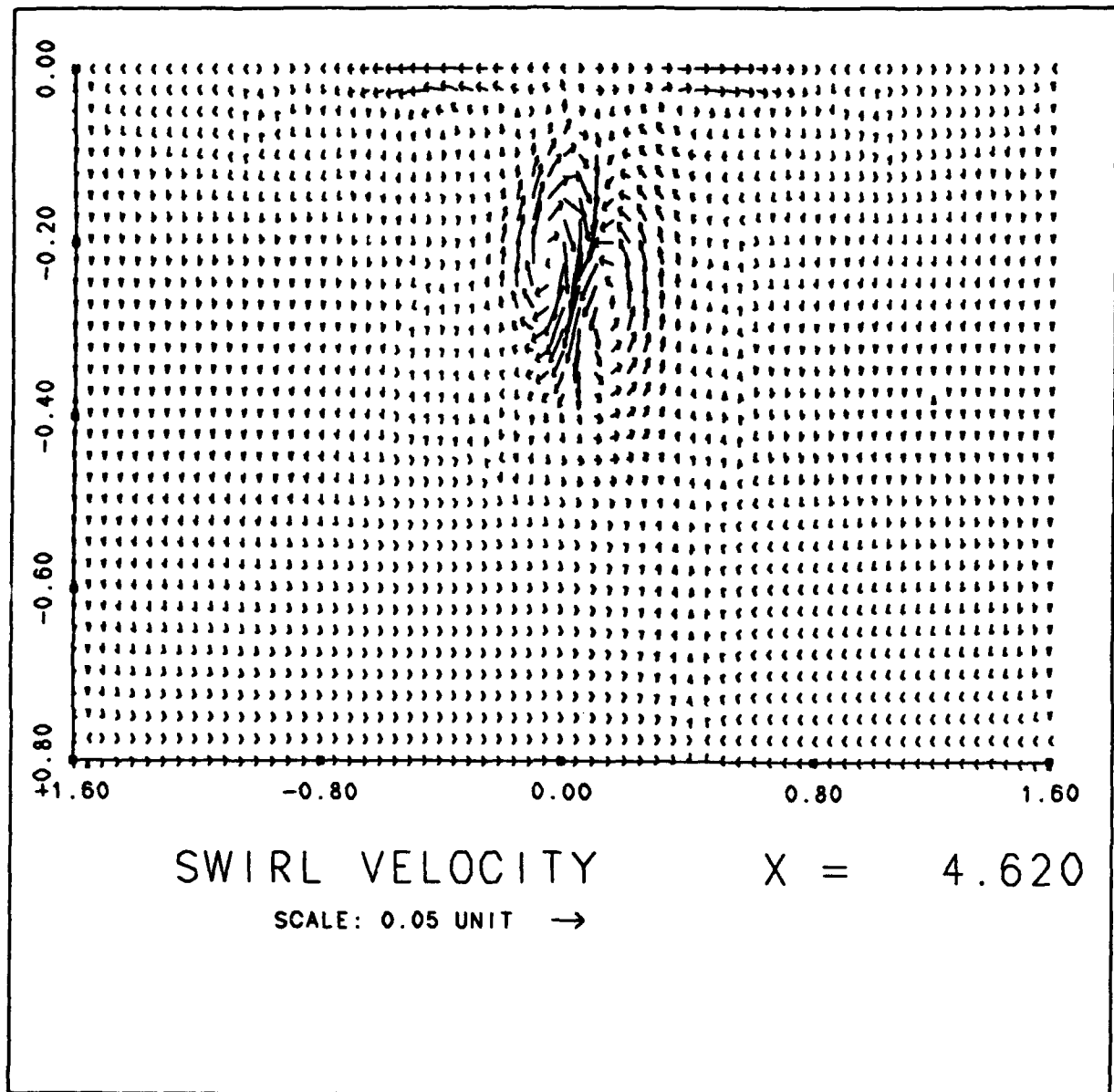
Figure 9.   Configuration 71: Swirl velocity plot at x/B=5.60 (Initial plane)
Distances in beams
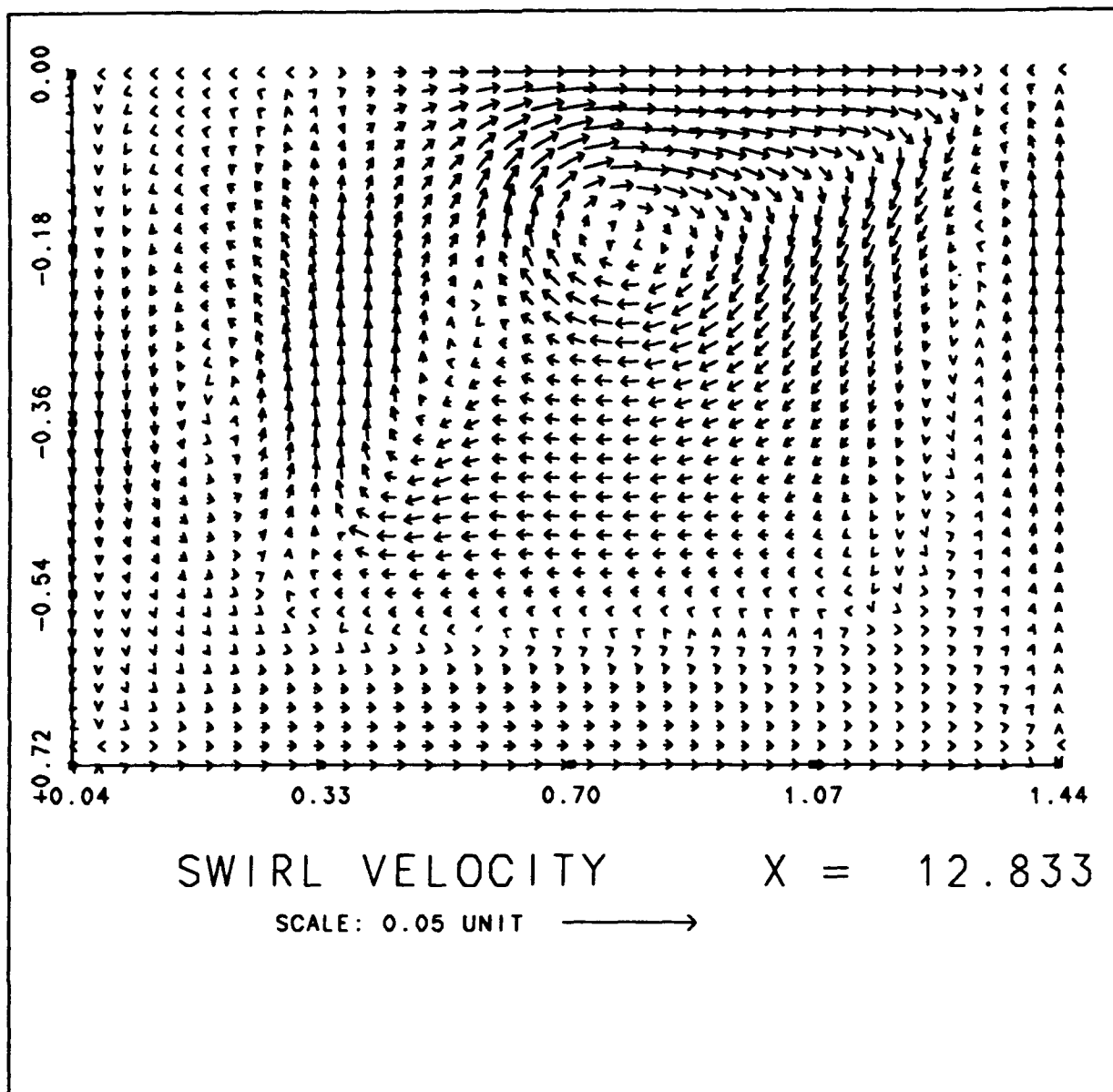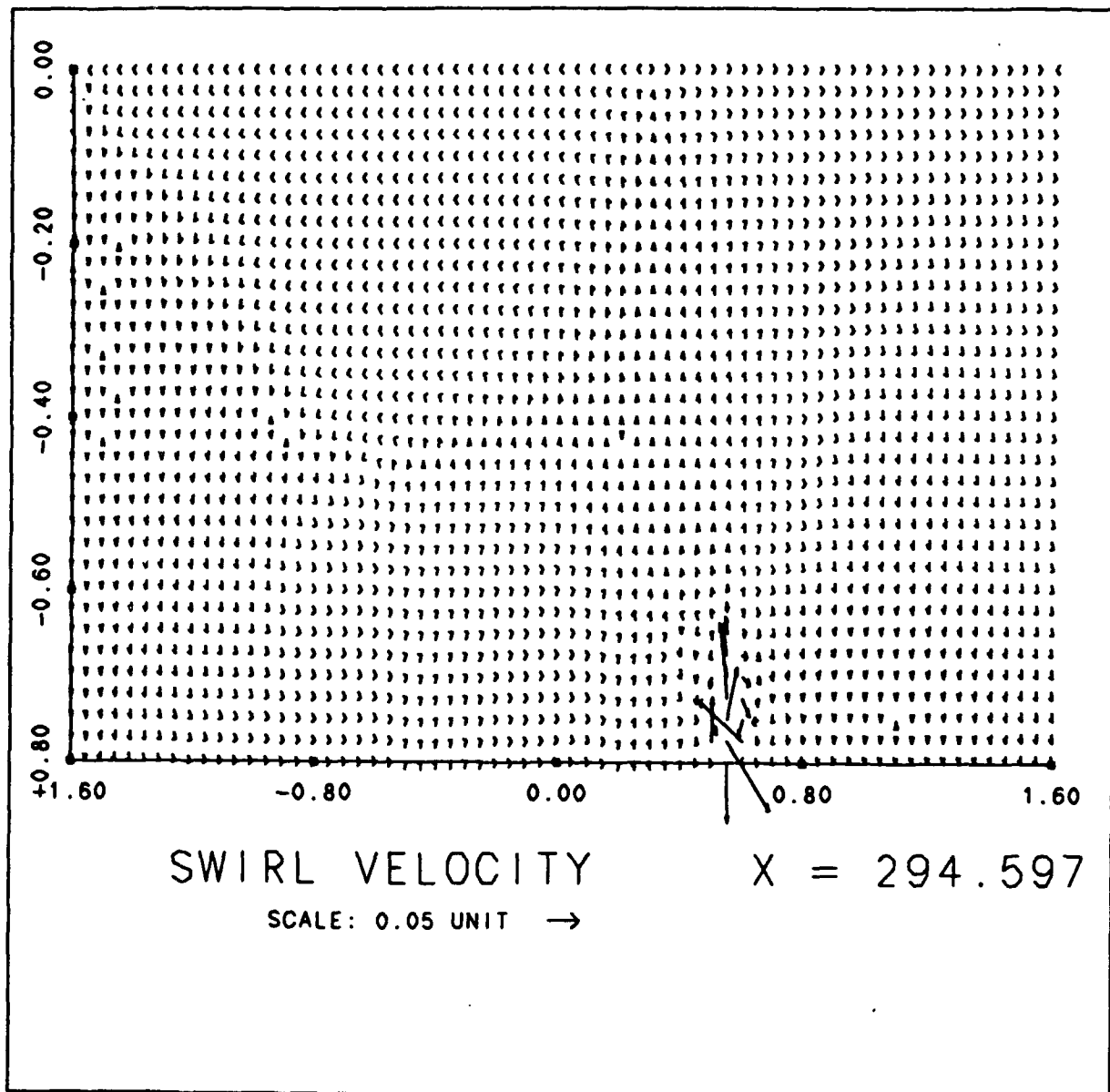
Figure 10.   Configuration 71: Swirl velocity plot at x/B=12.833
Distances in beams
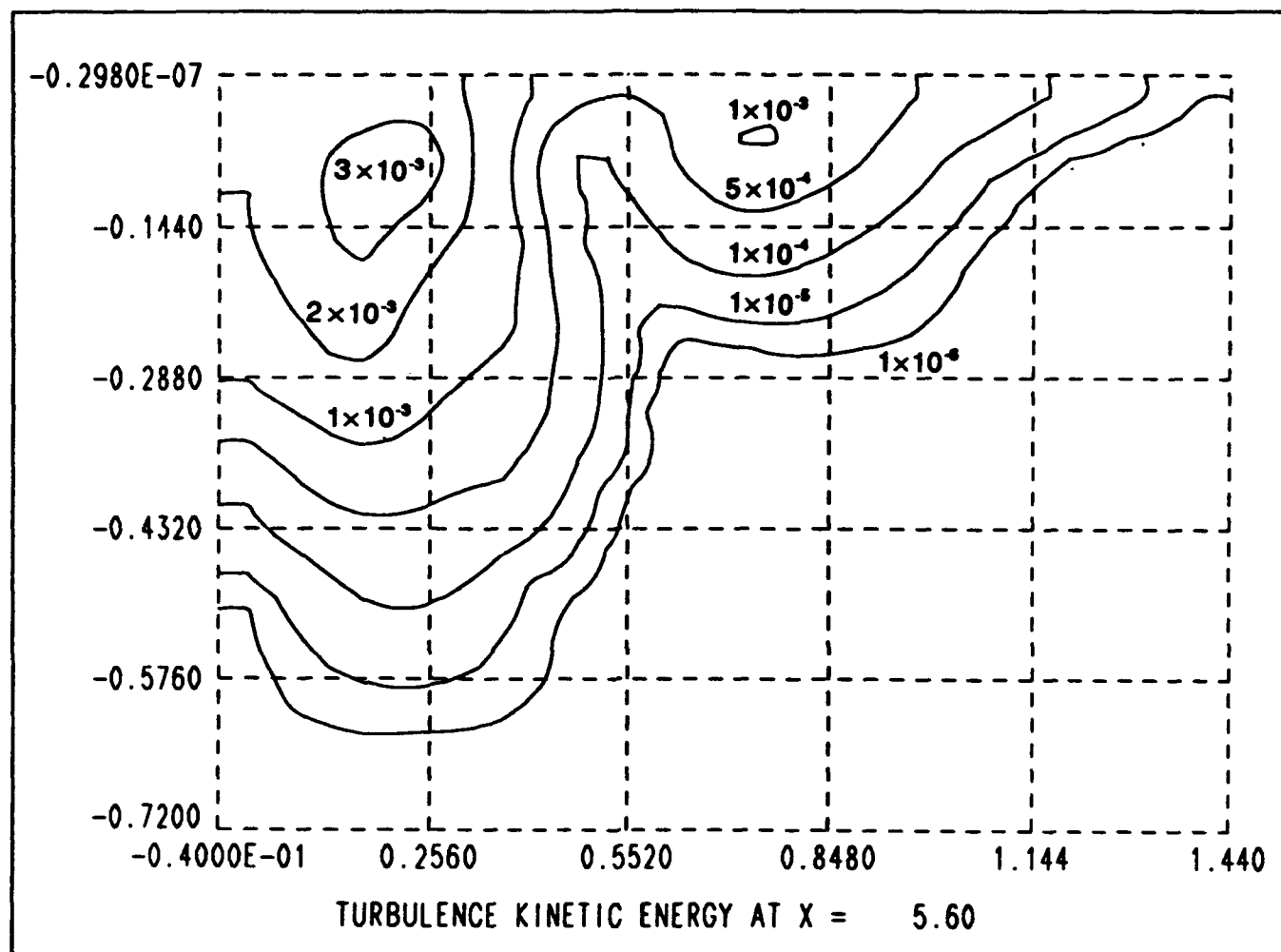
Figure 11.   Configuration 71: Turbulence kinetic energy at x/B=5.60
             (Initial plane)
             Distances in beams
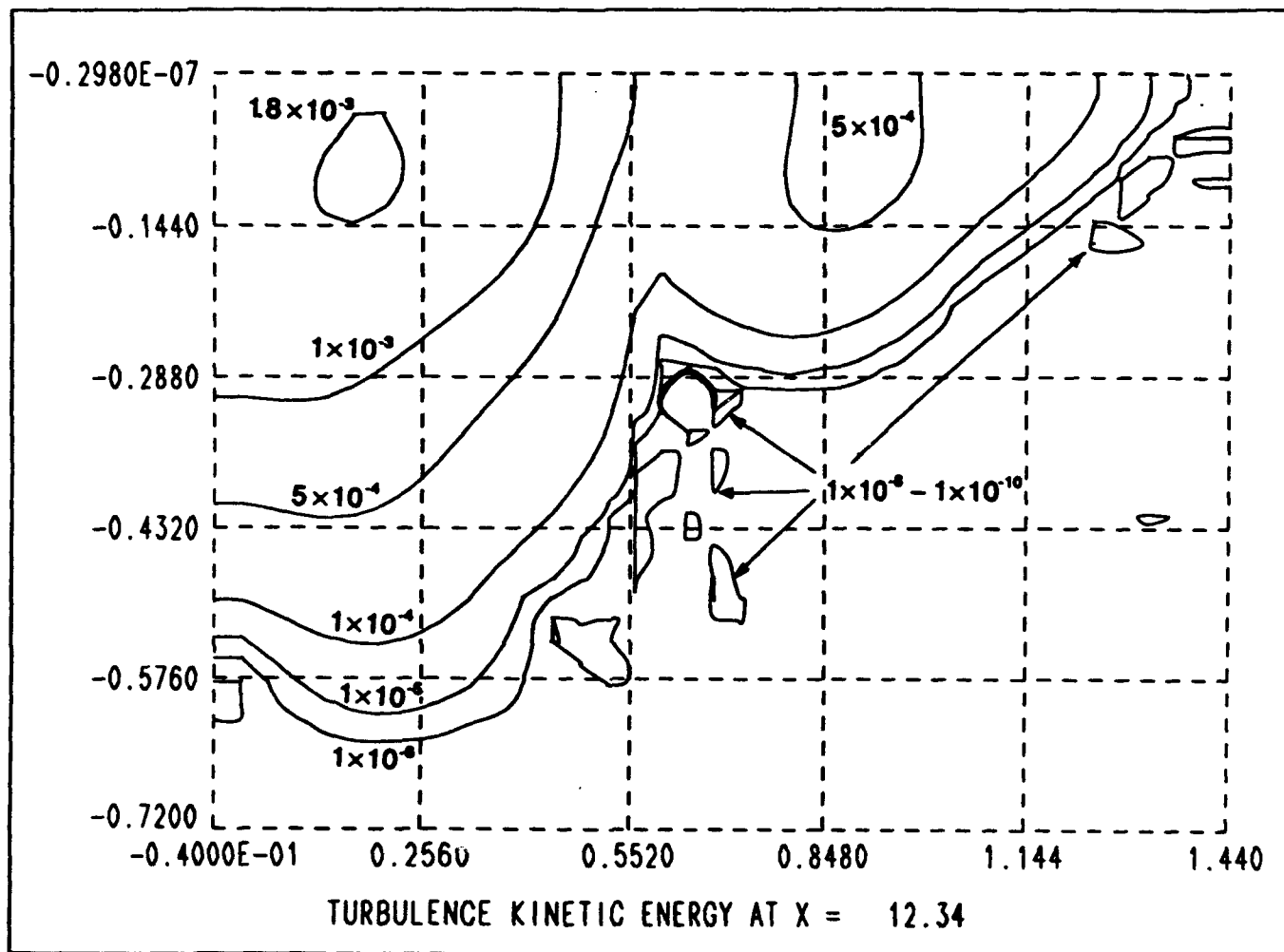
Figure 12. Configuration 71: Turbulence kinetic energy at x/B=12.34
Distances in beams

REYNOLDS STRESS   X =   5.600

SCALE: 0.0005 UNIT →
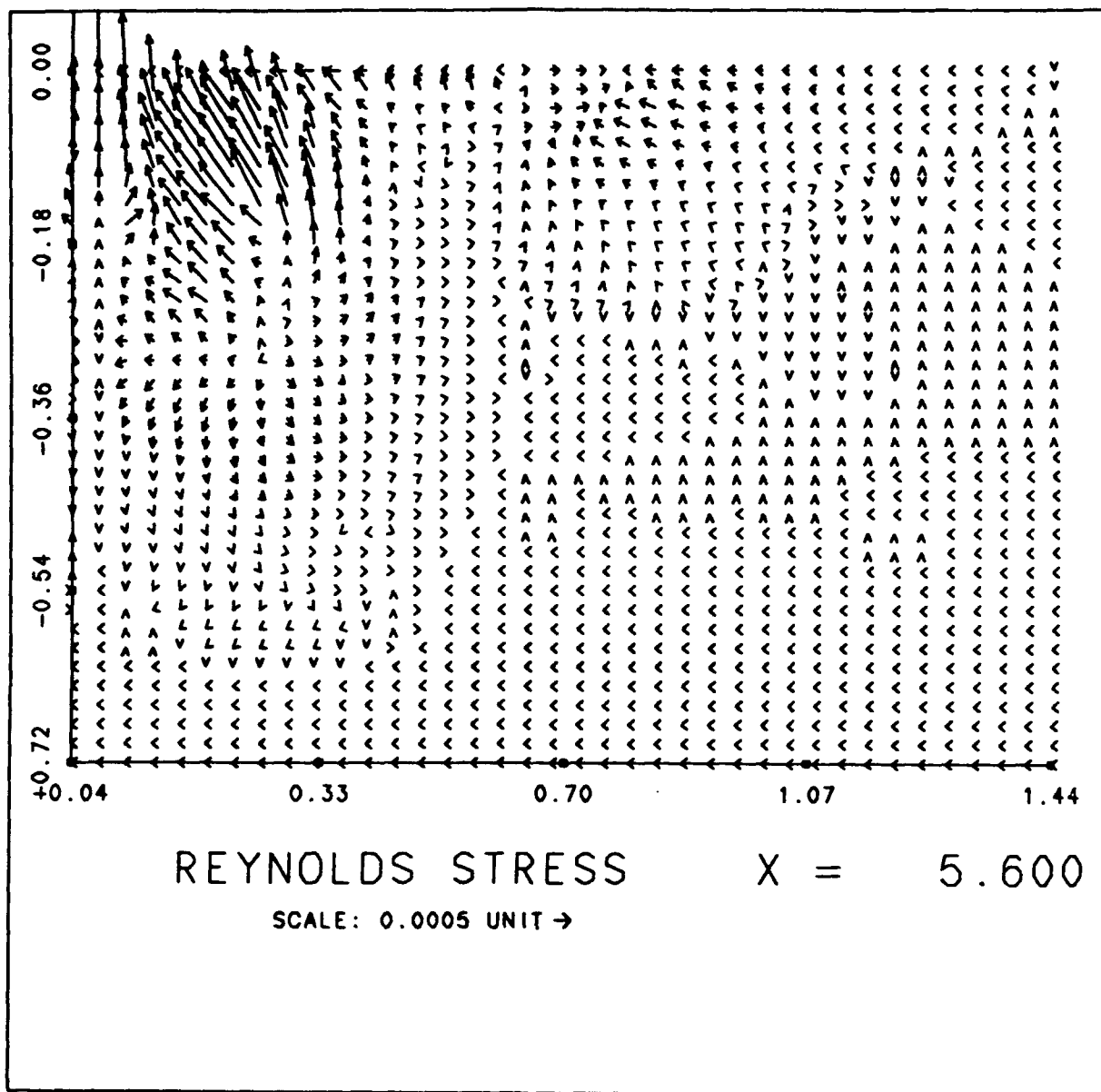
Figure 13.   Configuration 71: Reynolds stress plot at x/B=5.60 (Initial plane)
              Distances in beams
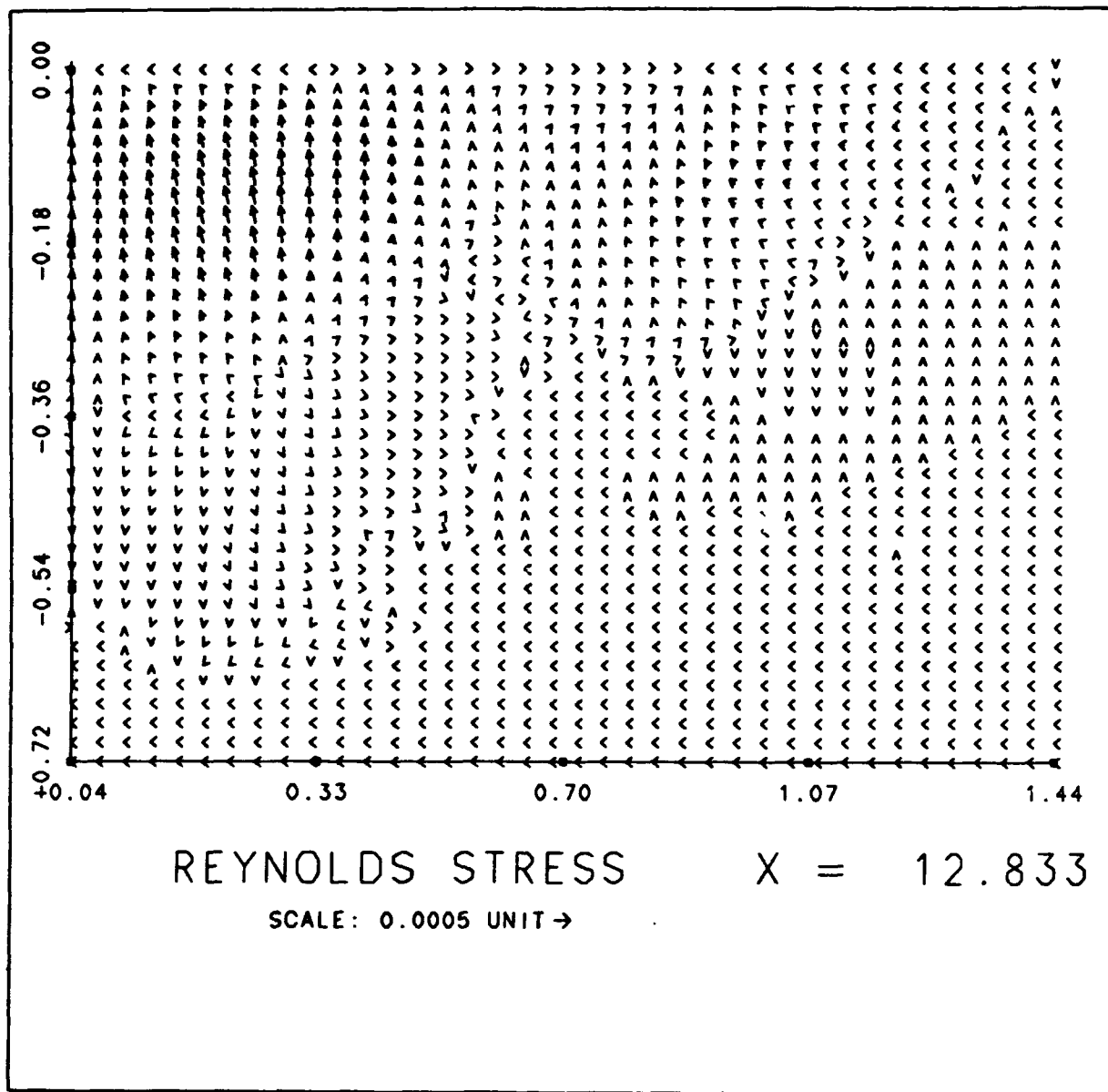
Figure 14. Configuration 71: Reynolds stress plot at x/B=12.833
Distances in beams
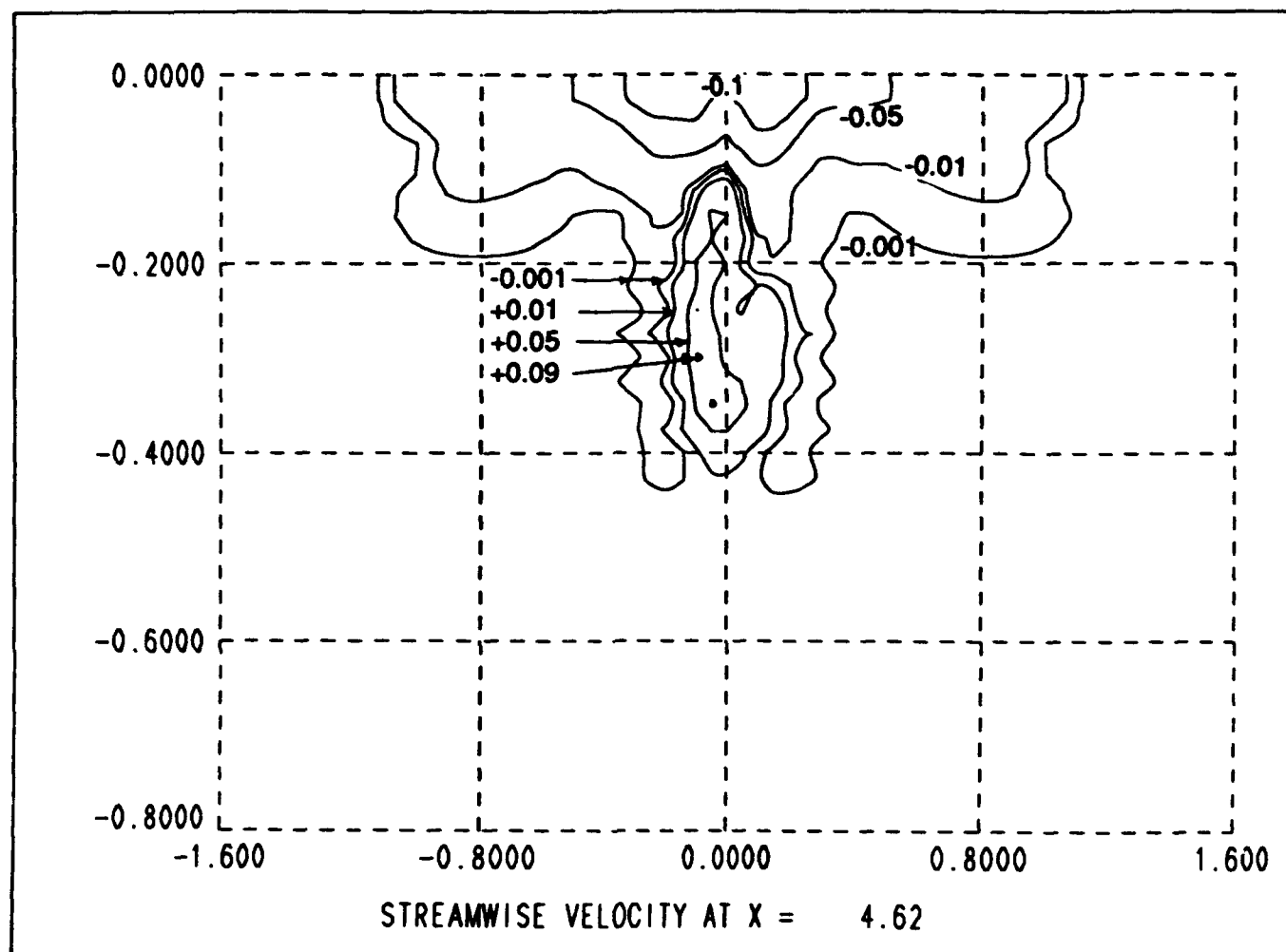
Figure 15.   Configuration 81: Streamwise velocity at x/B=4.62 (Initial plane)
               Distances in beams
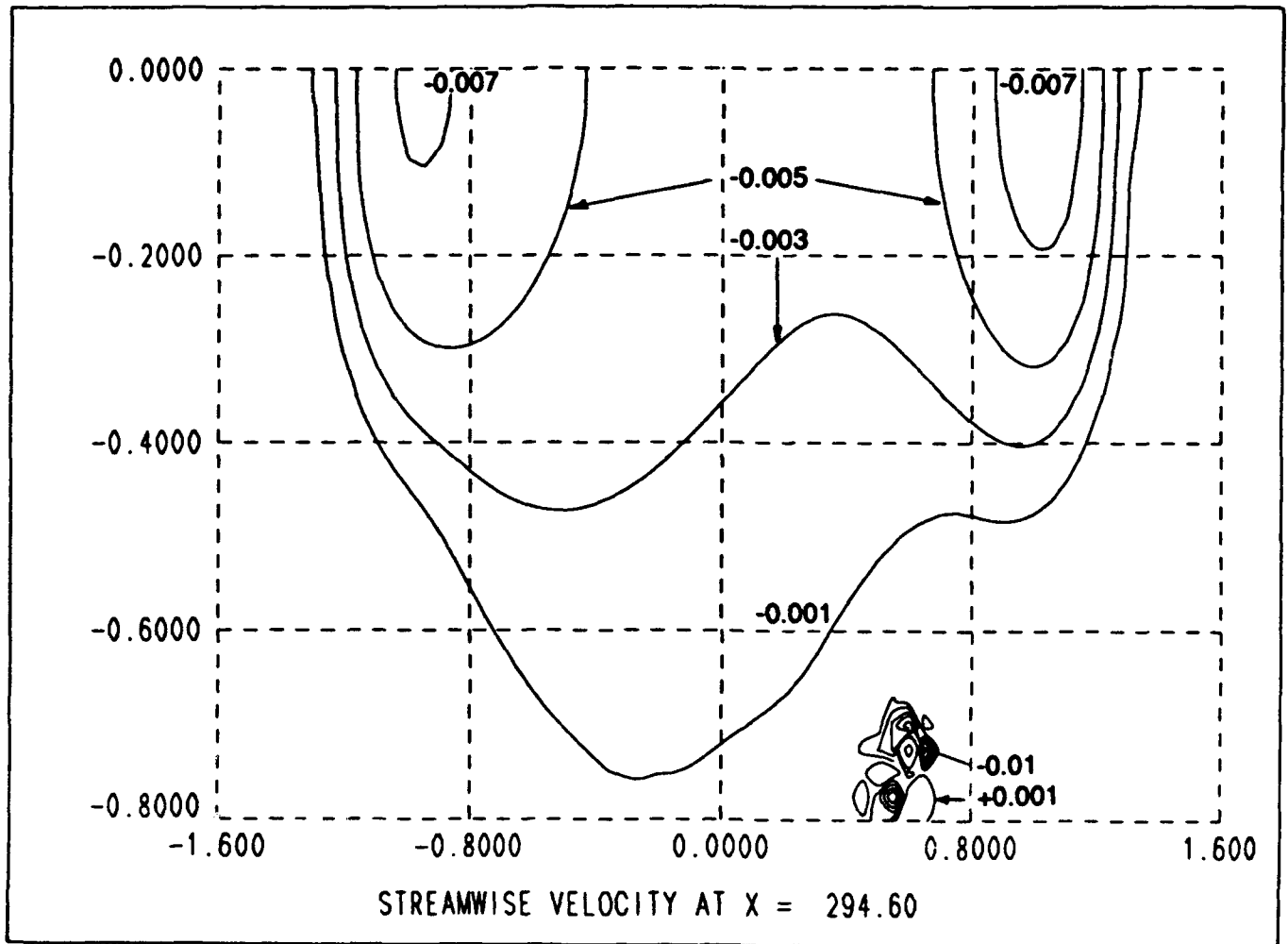
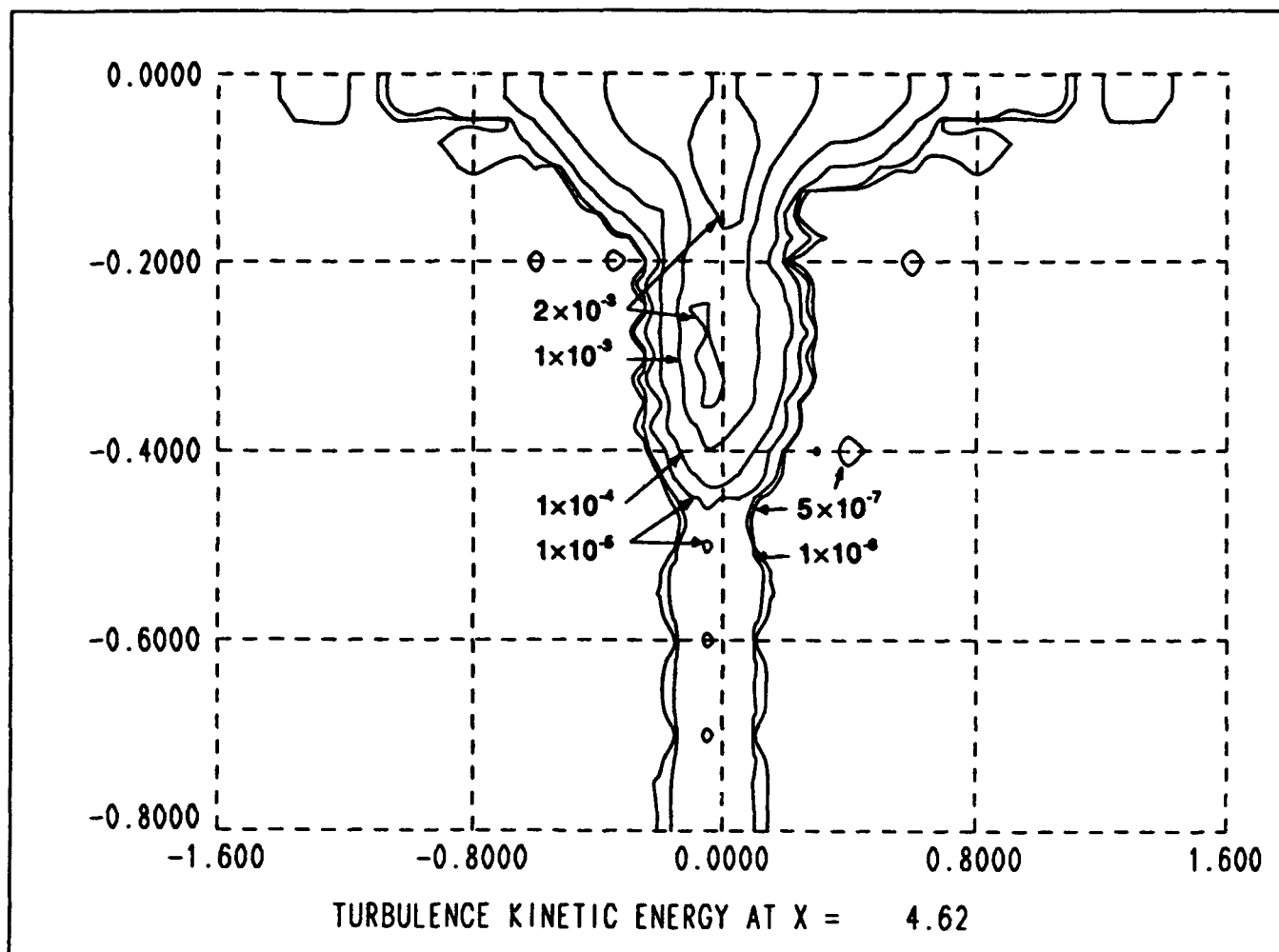Figure 16.   Configuration 81: Streamwise velocity at x/B=294.60
Distances in beams
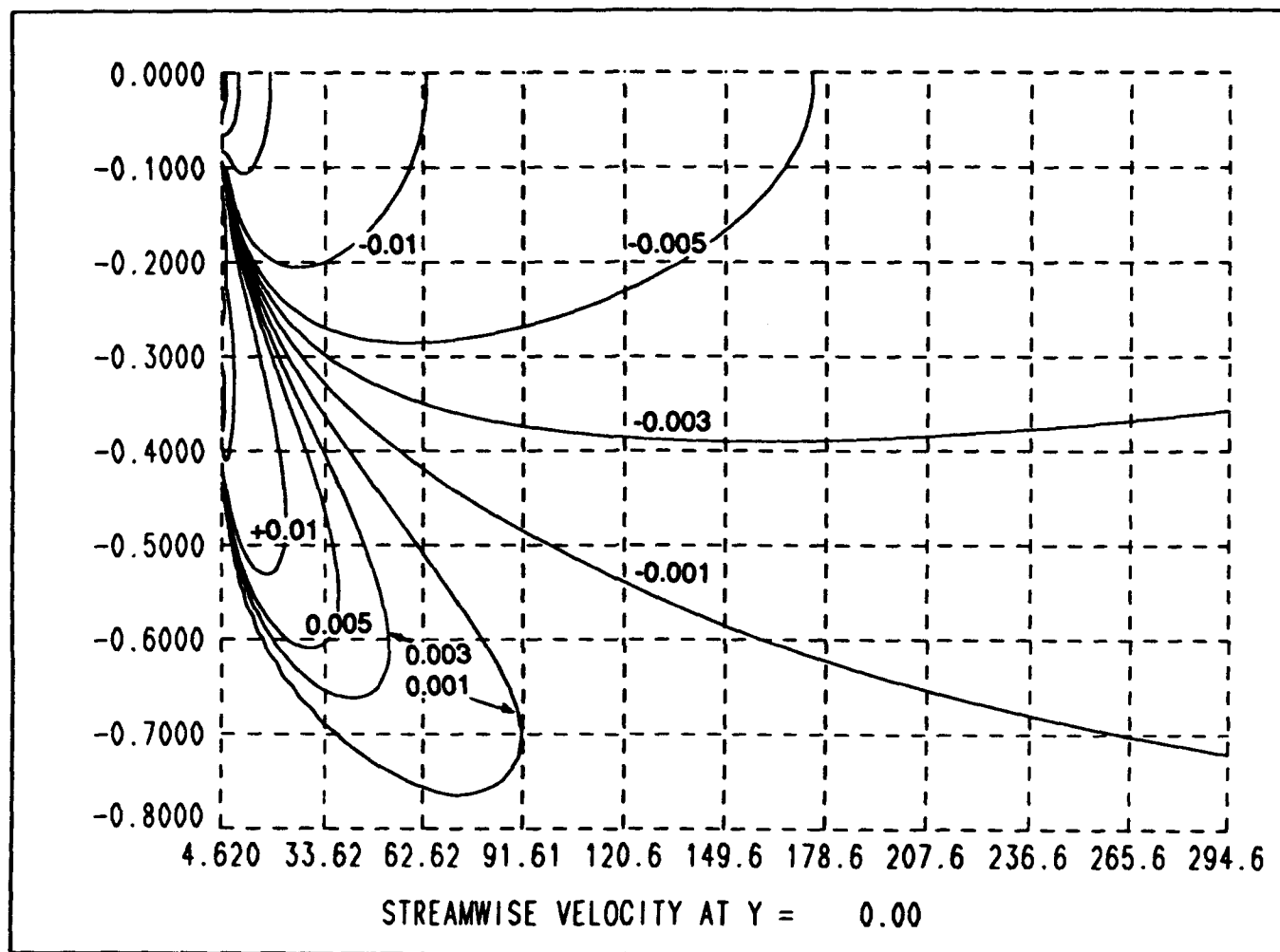
Figure 17. Configuration 81: Streamwise velocity at y/B=0.0
Distances in beams

Figure 18.   Configuration 81: Streamwise velocity at z/B=0.0
              Distances in beams

| -0.0267 |
| 0.04959 |
| 0.02304 |
| 0.07886 |
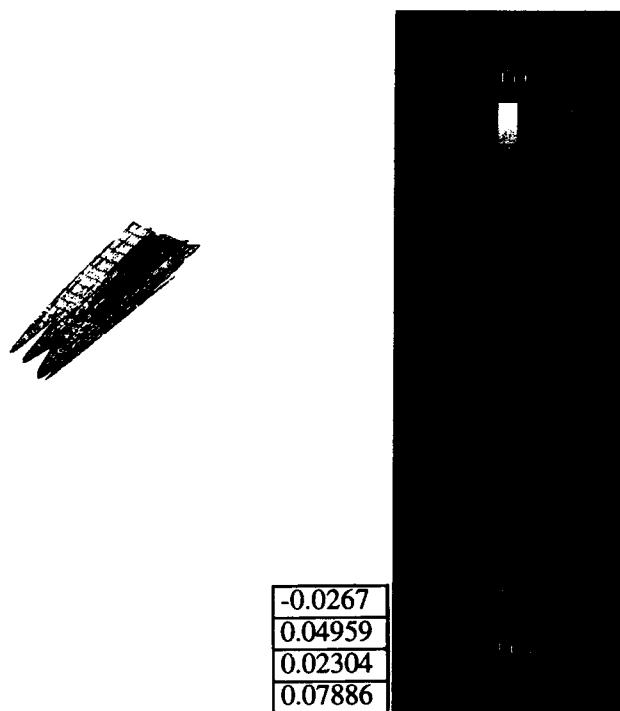
Figure 19. Configuration 81: Iso-surfaces of streamwise velocity in the
near-field wake: x/B = 4.62 to 37.70
Distances in beams; PMIN=-0.14783, PMAX=0.09436

| -0.0267 |
| 0.04959 |
| 0.02304 |
| 0.07886 |
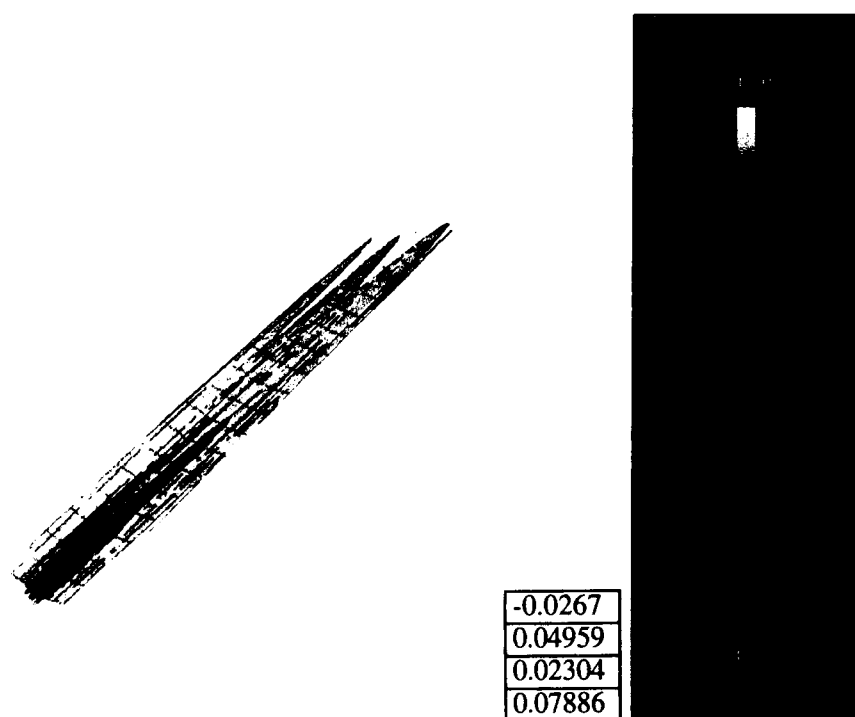
Figure 20. Configuration 81: Iso-surfaces of streamwise velocity in the
near-field wake: x/B = 4.62 to 37.70
Distances in beams; PMIN=-0.14783, PMAX=0.09436

-0.0199
-0.0054
-0.0043
0.01281
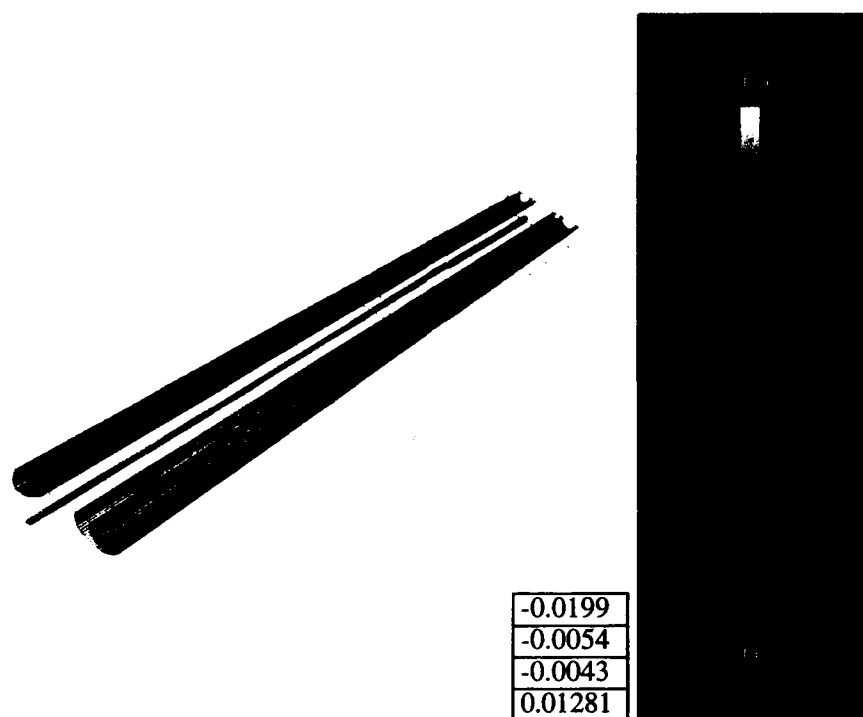
Figure 21. Configuration 81: Iso-surfaces of streamwise velocity in the far-field wake: x/B = 262.9 to 294.59
Distances in beams; PMIN=-0.03207, PMAX=0.0212

-0.0199
-0.0054
-0.0043
0.01281
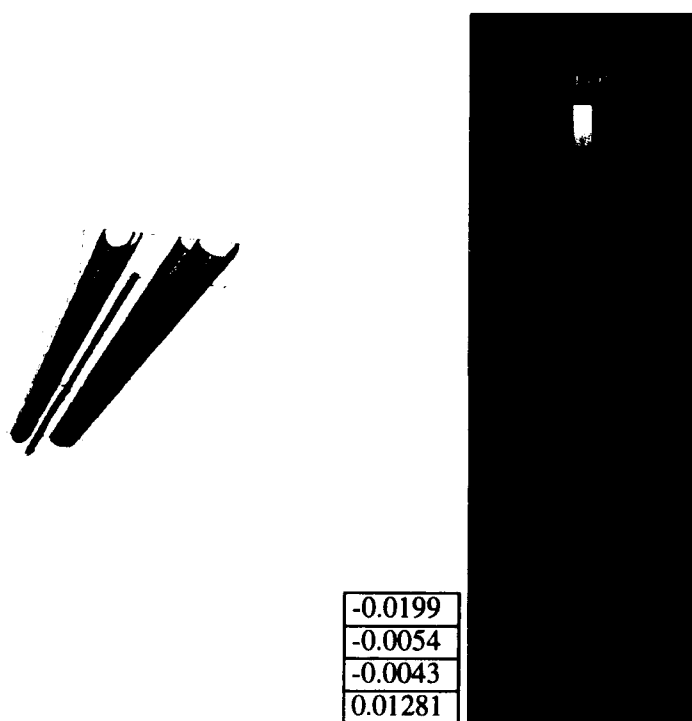
Figure 22. Configuration 81: Iso-surfaces of streamwise velocity in the far-field wake: x/B = 262.9 to 294.59
Distances in beams; PMIN=-0.03207, PMAX=0.0212

Figure 23.   Configuration 81: Swirl velocity plot at x/B=4.62 (Initial plane)
Distances in beams

Figure 24.   Configuration 81: Swirl velocity plot at x/B=294.59
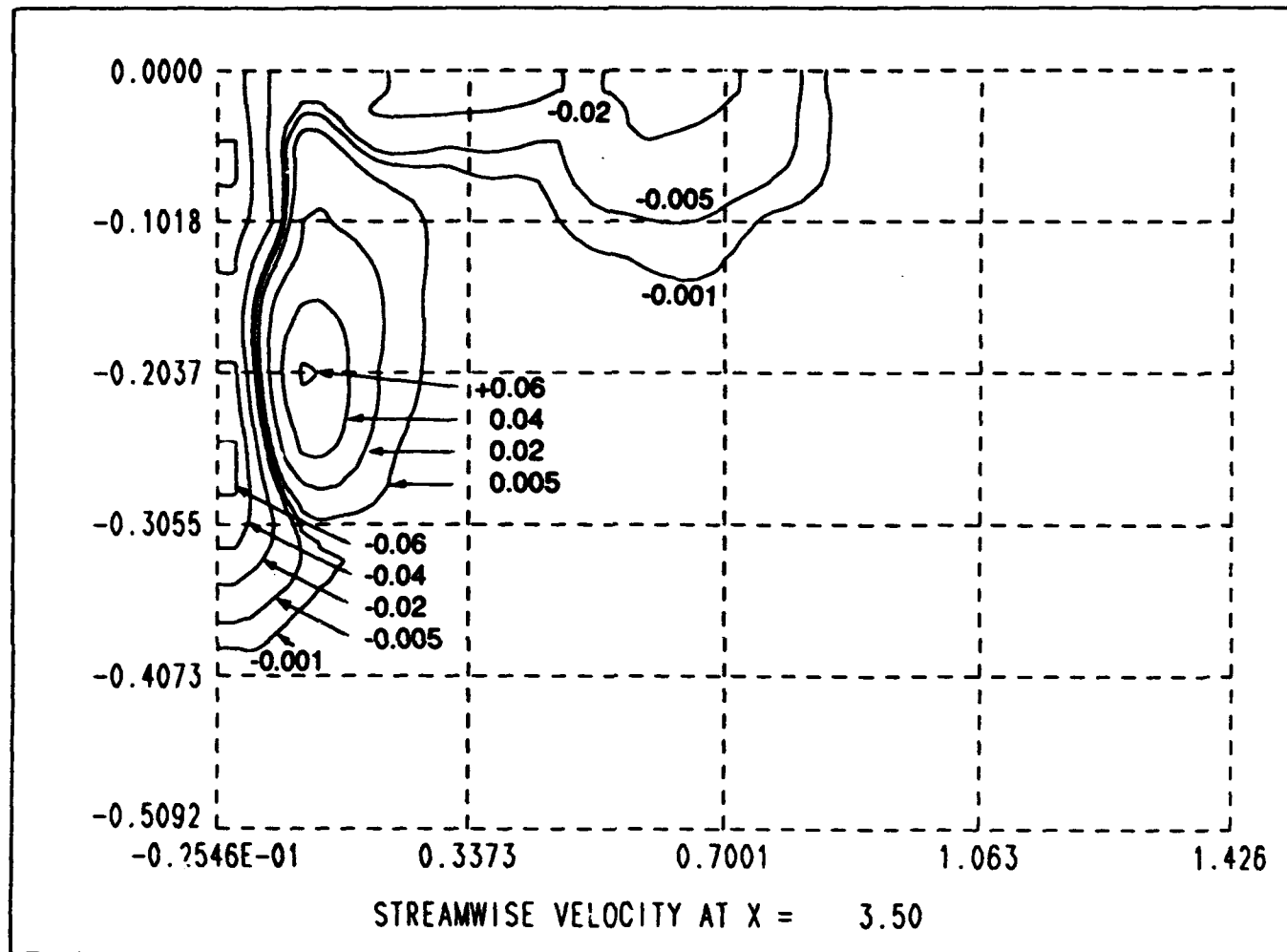   Distances in beams

Figure 25.   Configuration 81: Turbulence kinetic energy at x/B=4.62
(Initial plane)
Distances in beams
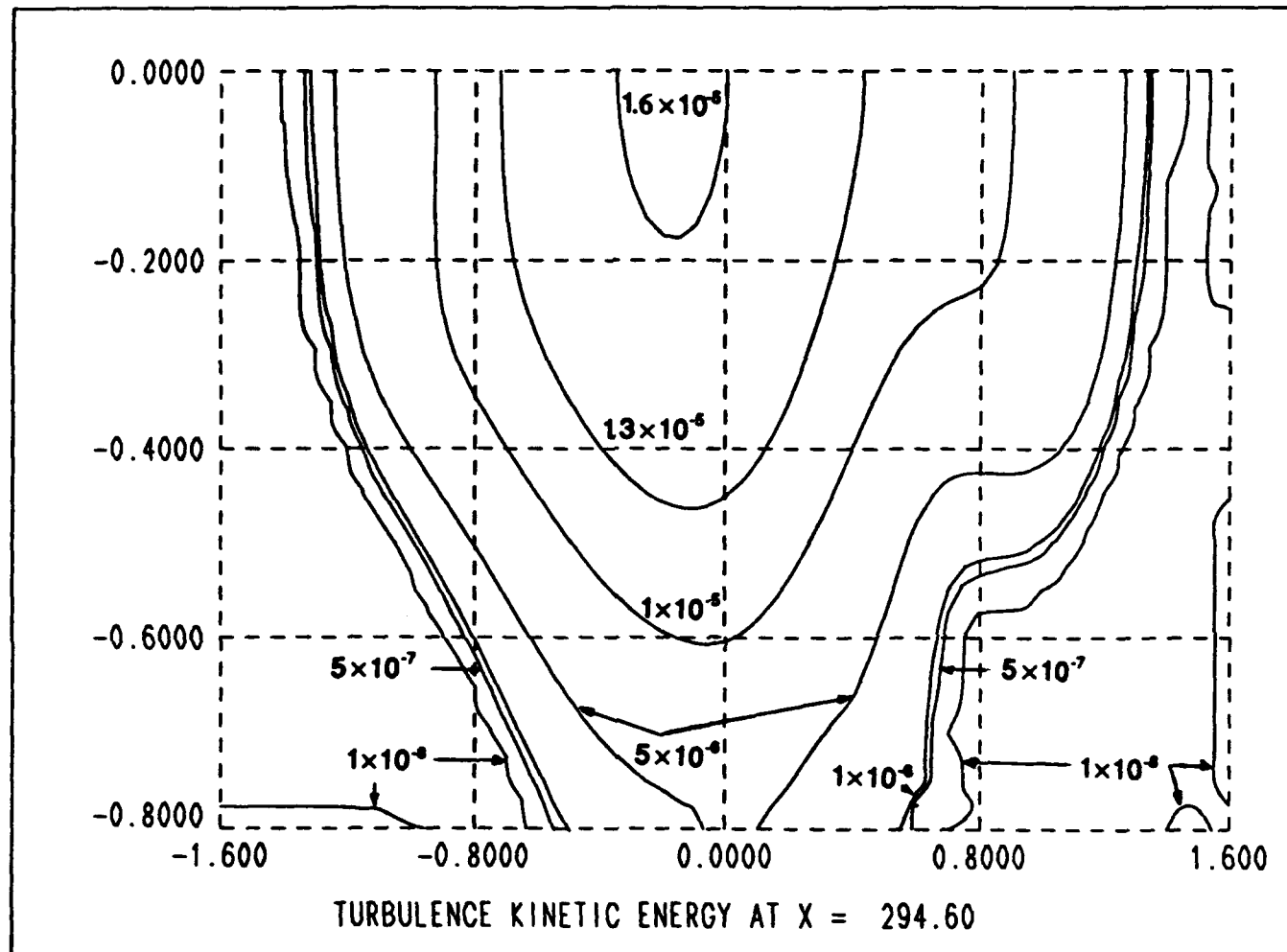
Figure 26.   Configuration 81: Turbulence kinetic energy at x/B=294.59
Distances in beams
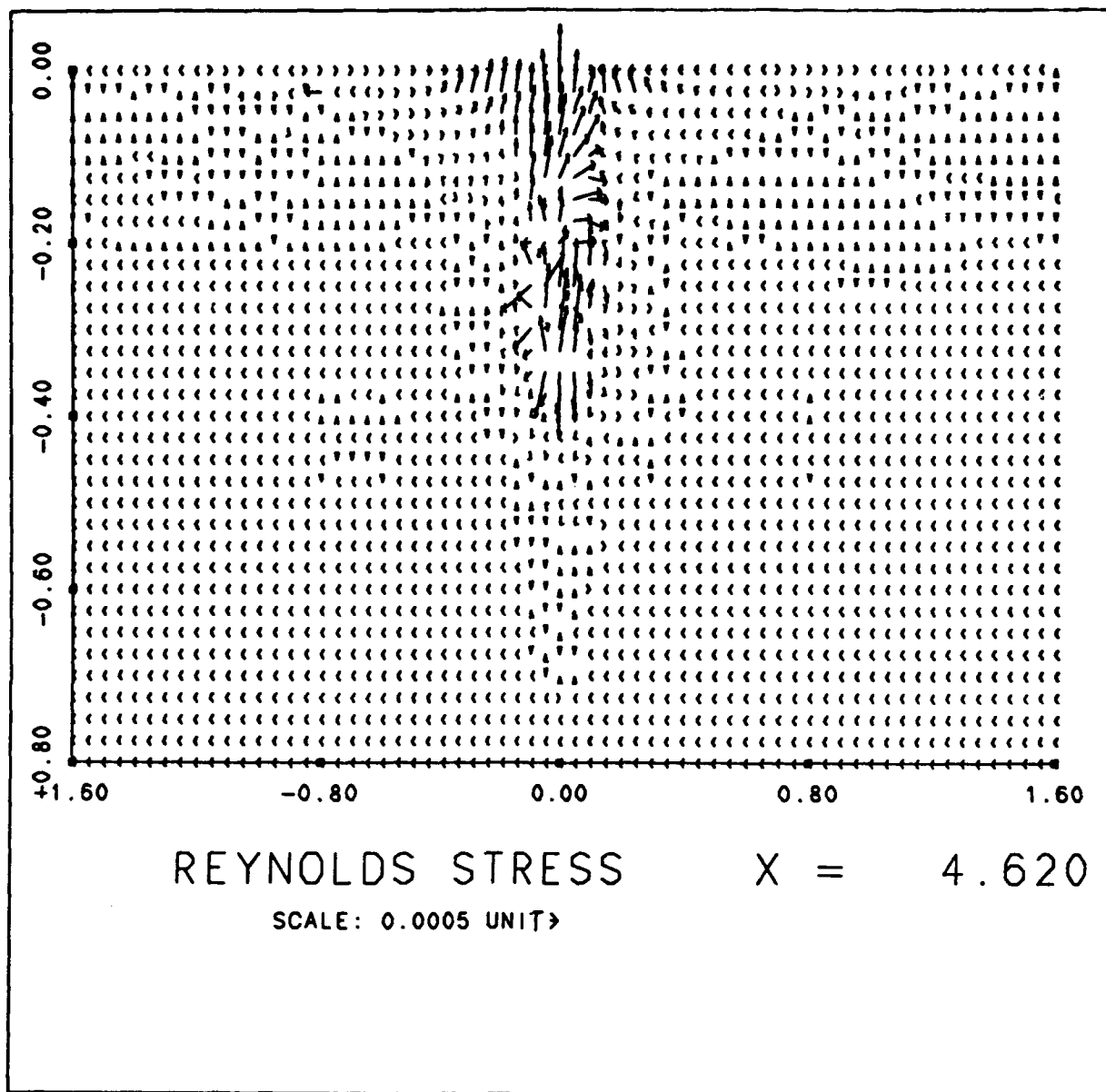
Figure 27.   Configuration 81: Reynolds stress plot at x/B=4.62 (Initial plane)
              Distances in beams

REYNOLDS STRESS   X = 294.597

SCALE: 0.0005 UNIT ⟶
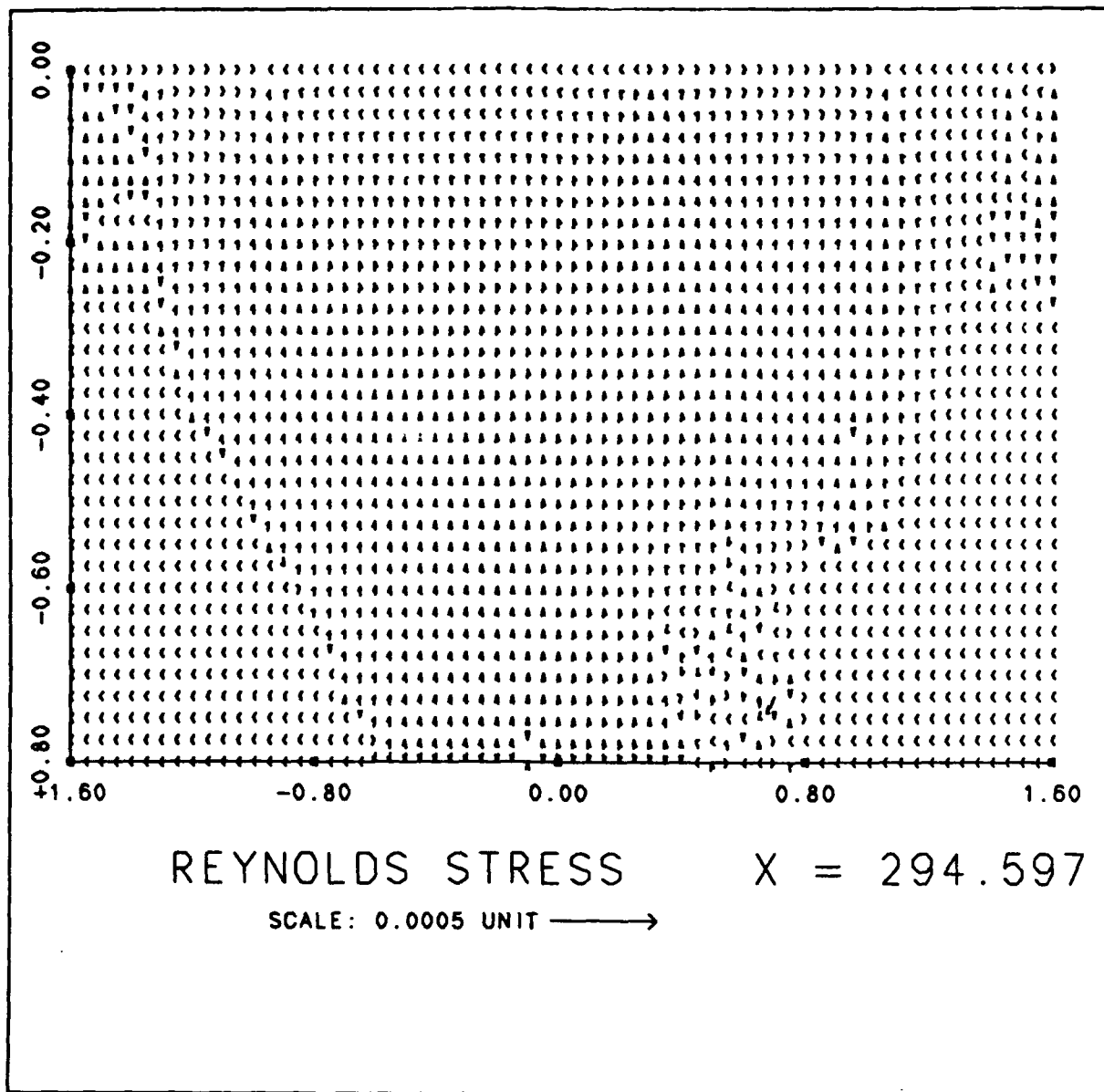
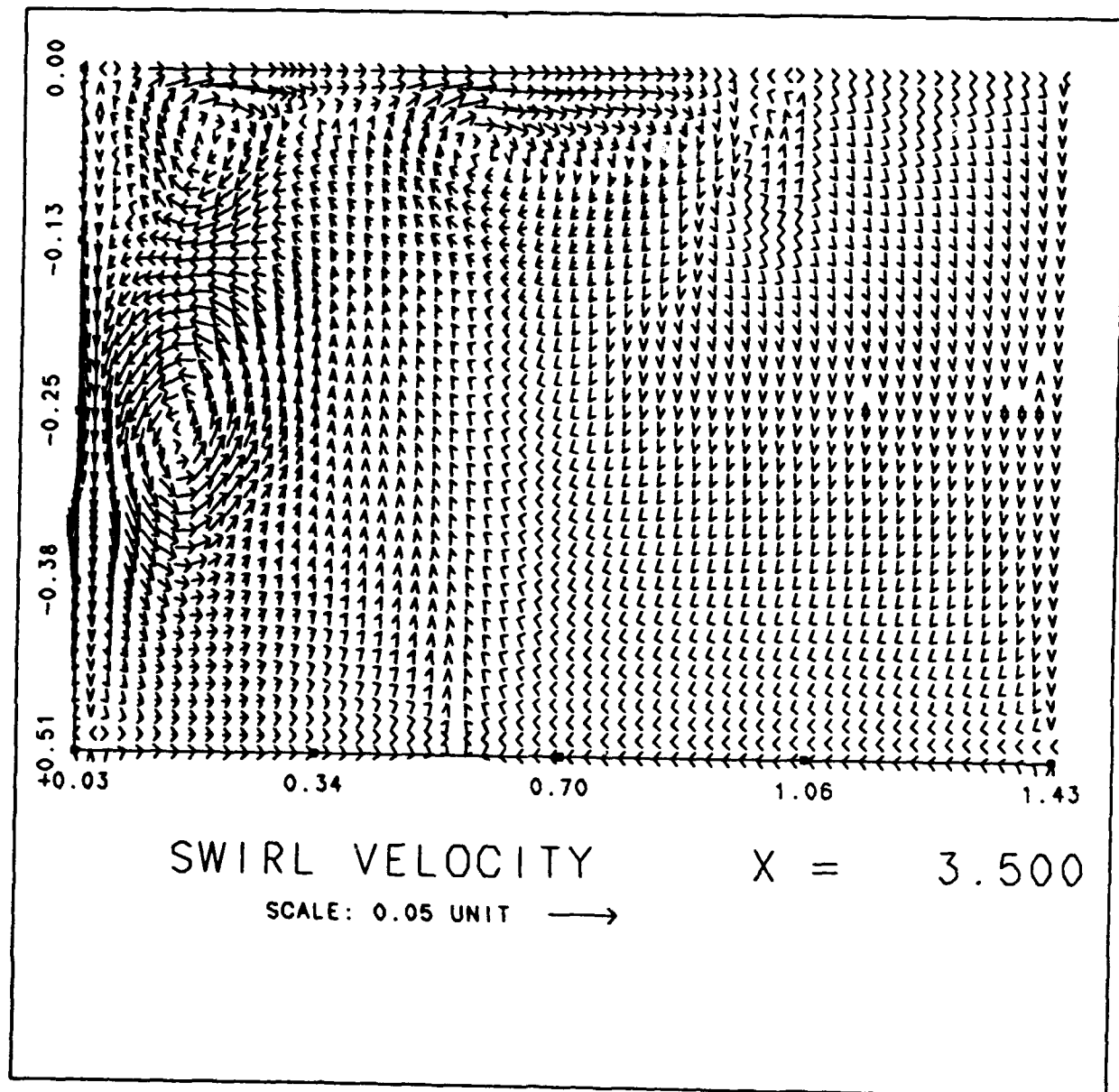Figure 28.   Configuration 81: Reynolds stress plot at x/B=294.59
Distances in beams

Figure 29. Configuration 61: Streamwise velocity at x/B=3.50 (Initial plane)
Distances in beams
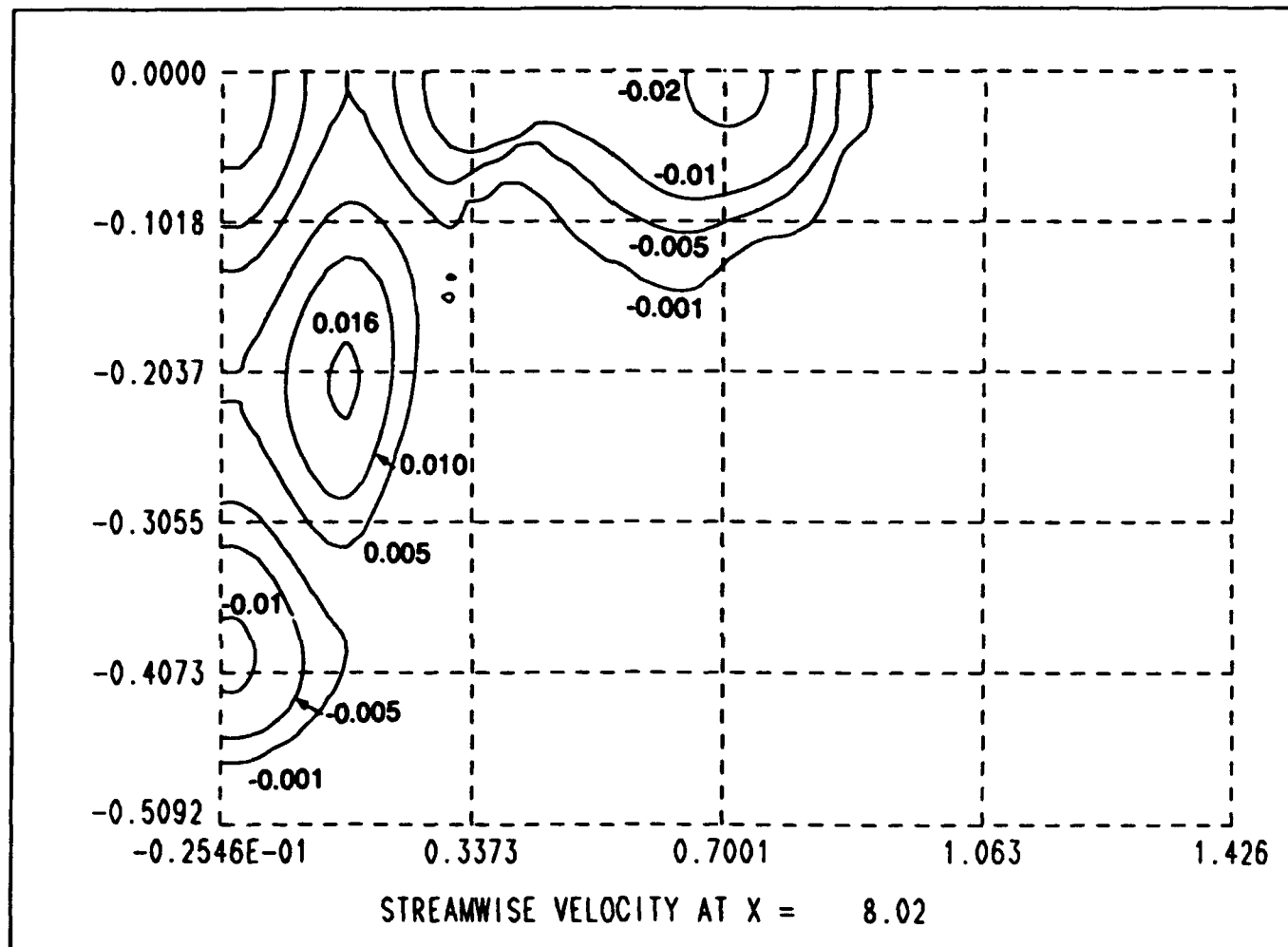
Figure 30.   Configuration 61: Streamwise velocity at x/B=8.02
Distances in beams

| -0.0482 |
| -0.0236 |
| 0.01248 |
| 0.02751 |
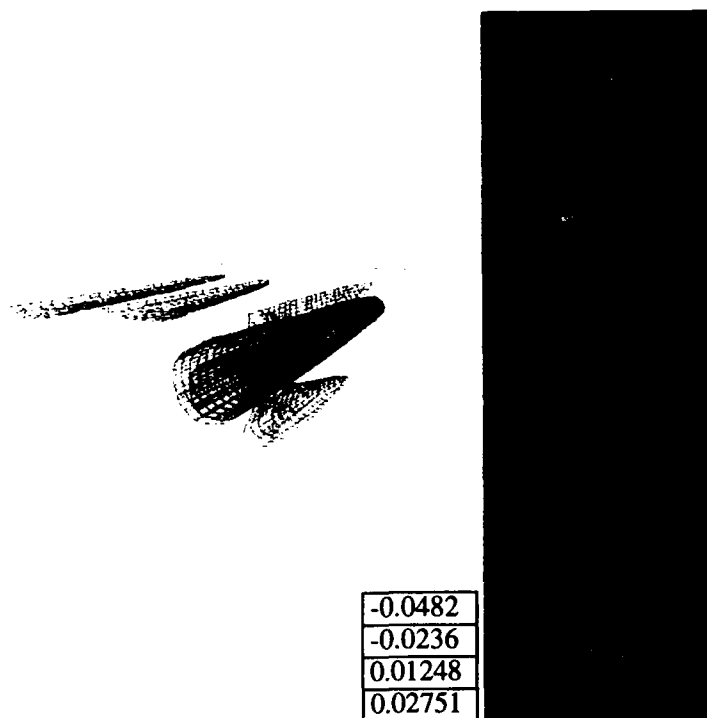
Figure 31. Configuration 61: Iso-surfaces of streamwise velocity
Distances in beams; PMIN=-0.0632, PMAX=0.0628

| -0.0482 |
| -0.0236 |
| 0.01248 |
| 0.02751 |
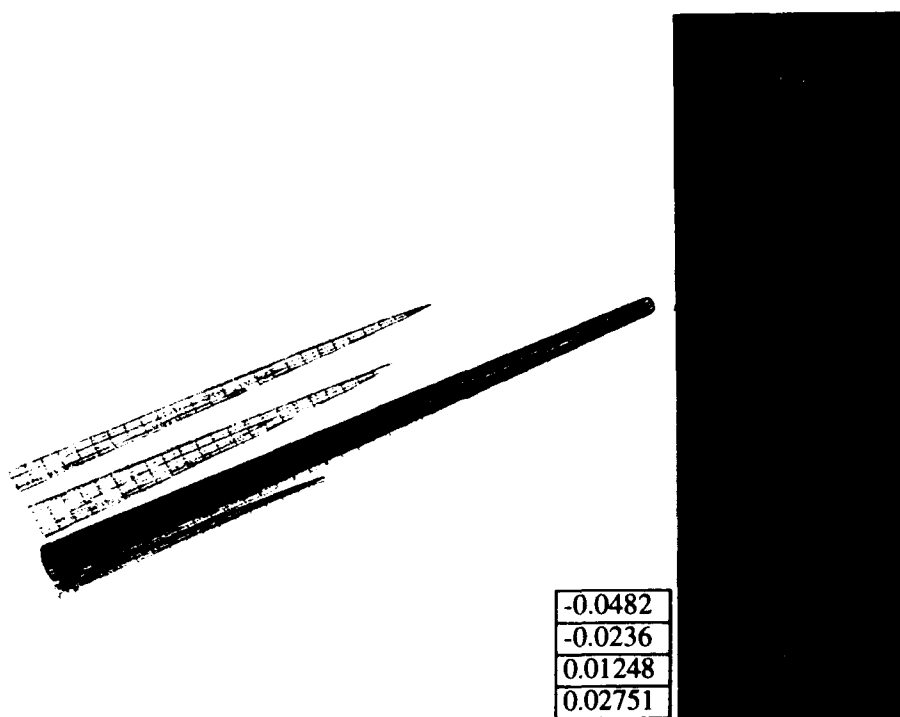
Figure 32. Configuration 61: Iso-surfaces of streamwise velocity
Distances in beams; PMIN=-0.0632, PMAX=0.0628

Figure 33. Configuration 61: Swirl velocity plot at x/B=3.50 (Initial plane)
Distances in beams
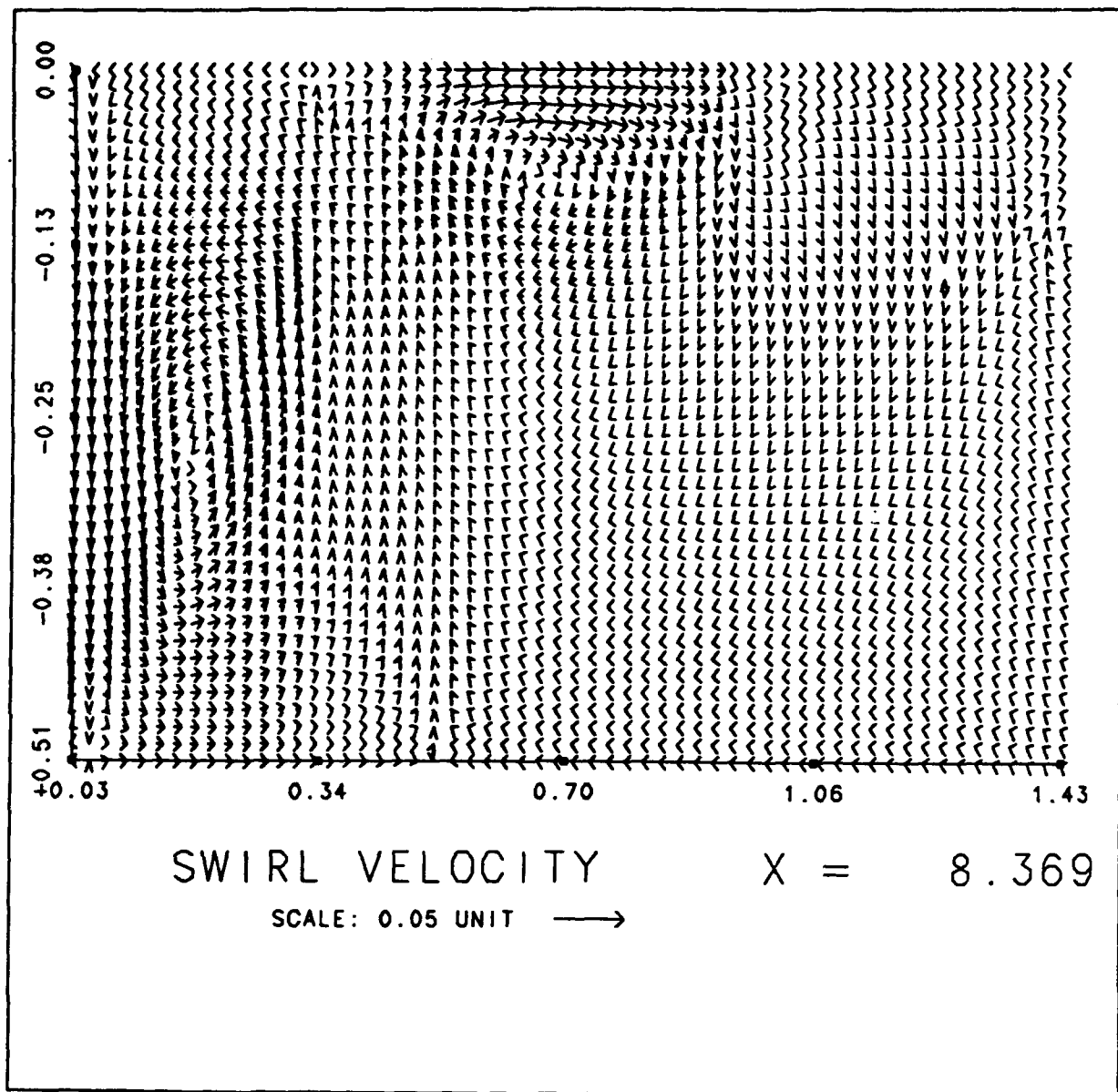
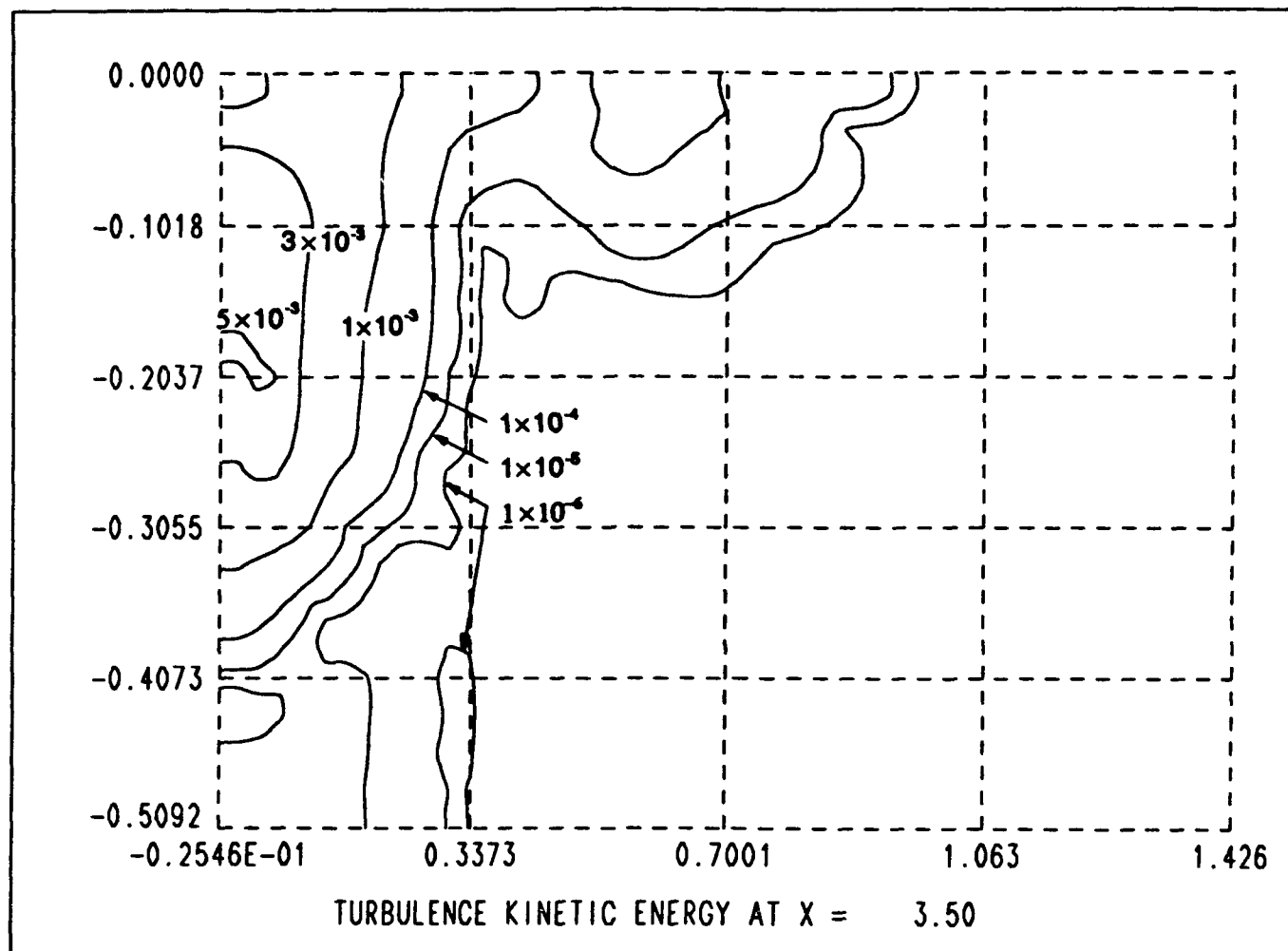**Figure 34.** Configuration 61: Swirl velocity plot at x/B=8.36
Distances in beams

Figure 35. Configuration 61: Turbulence kinetic energy at x/B=3.50
(Initial plane)
Distances in beams

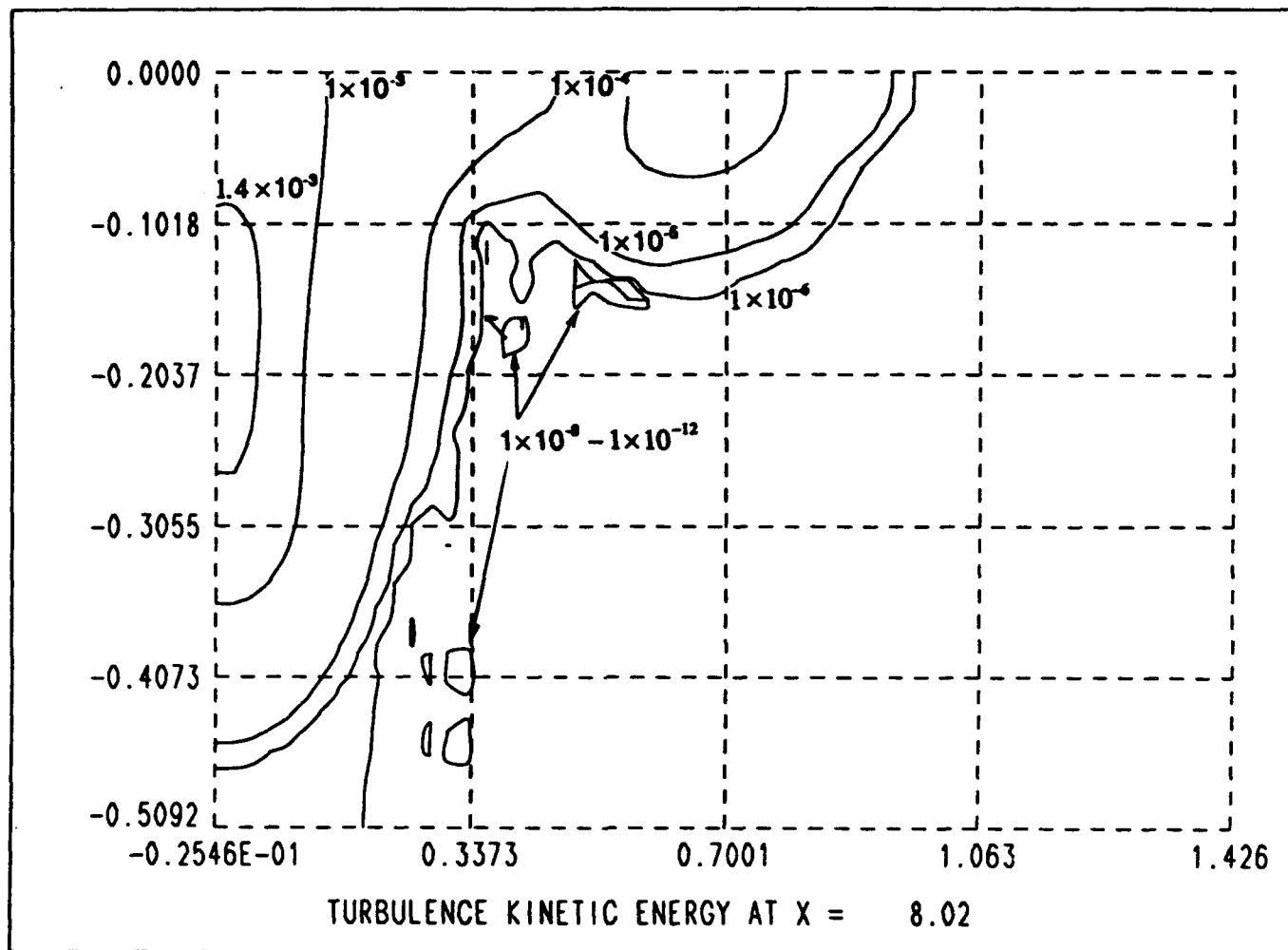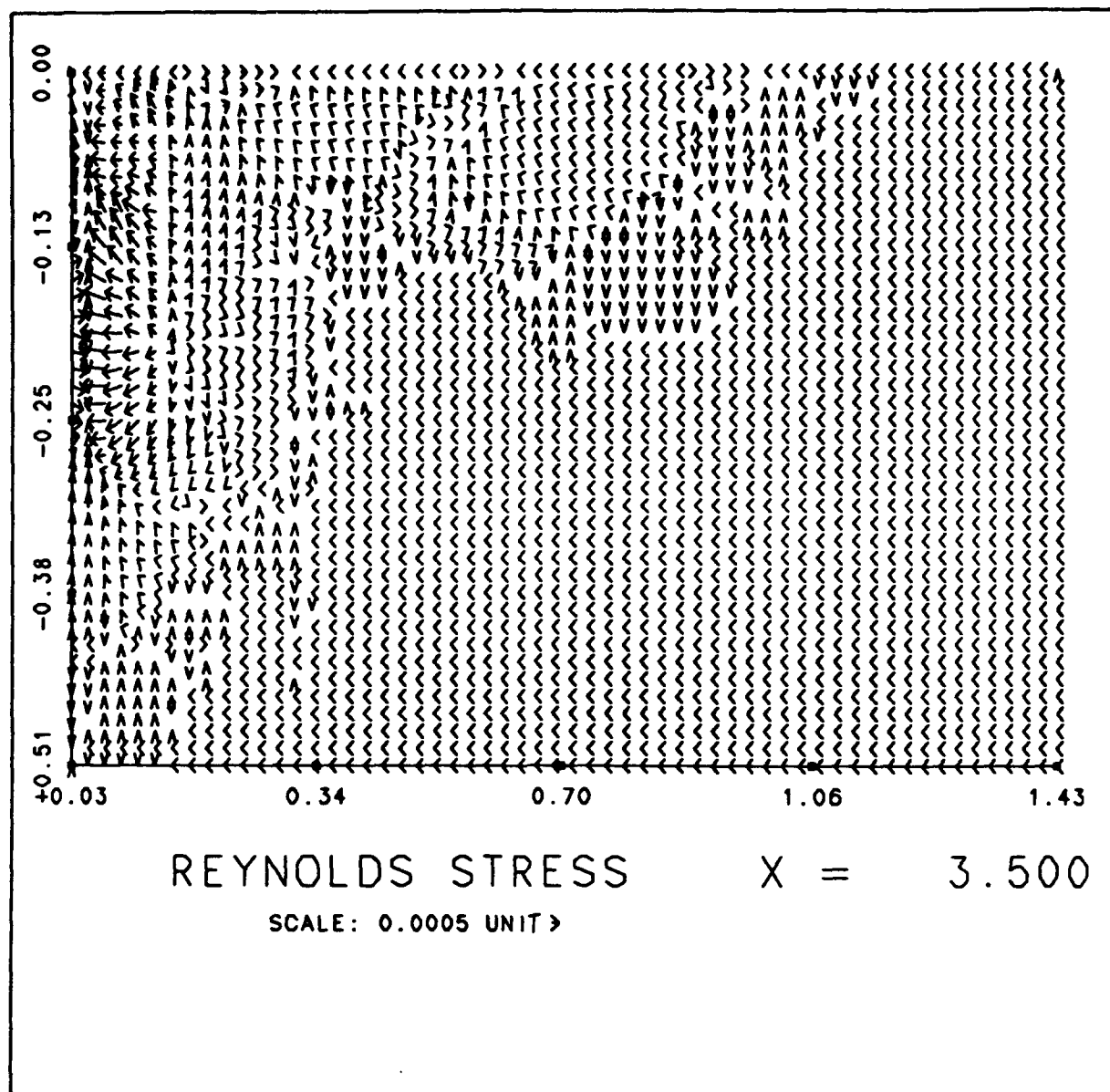Figure 36. Configuration 61: Turbulence kinetic energy at x/B=8.02
Distances in beams

REYNOLDS STRESS   X =   3.500

SCALE: 0.0005 UNIT >

Figure 37.   Configuration 61: Reynolds stress plot at x/B=3.50 (Initial plane)
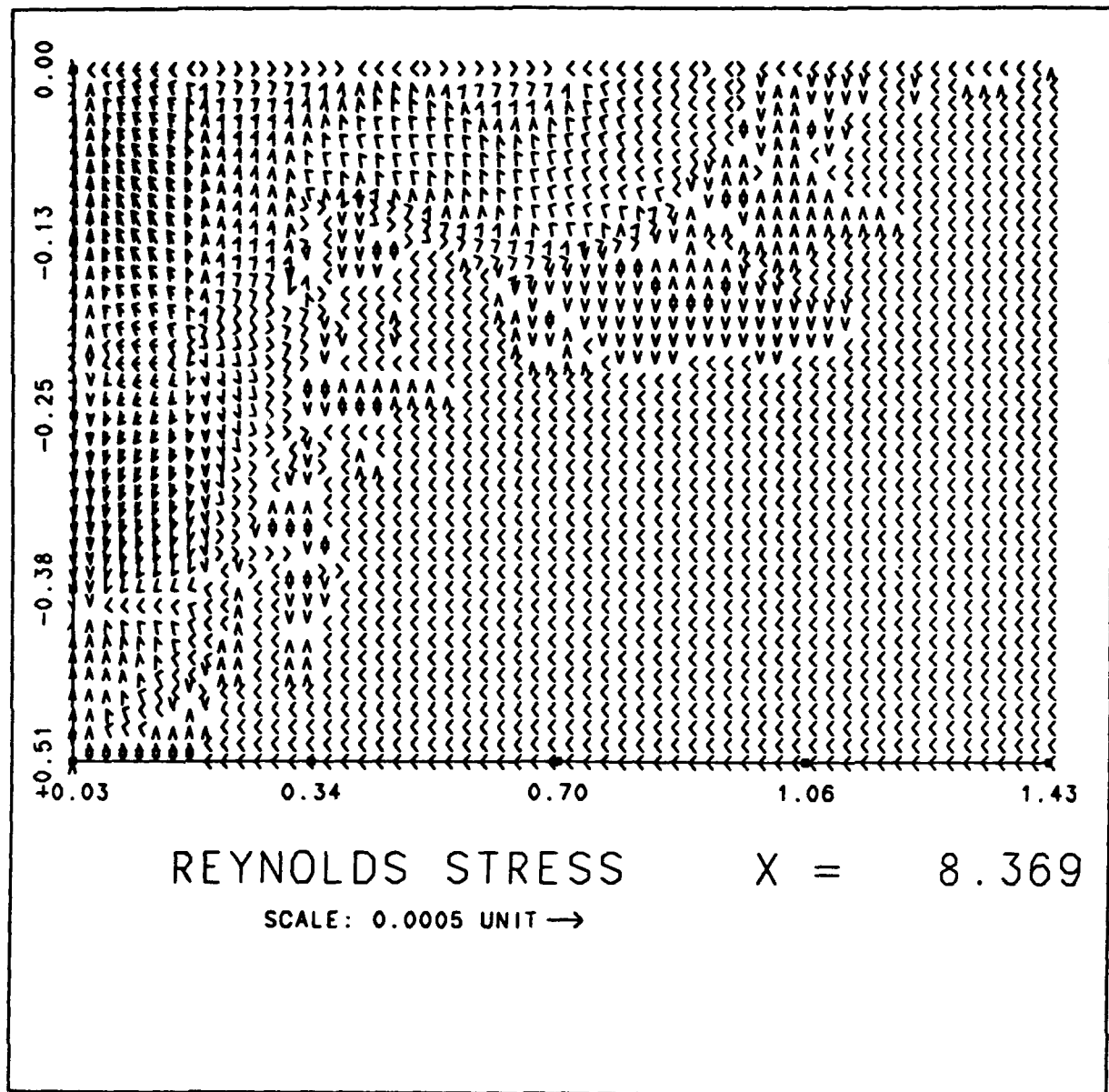   Distances in beams

Figure 38. Configuration 61: Reynolds stress plot at x/B=8.36
Distances in beams